

Equalization of Valve-Regulated Lead-Acid Batteries: Issues and Life Test Results

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Abstract:

The importance of state-of-charge (SOC) balance, or equalization, is well known. Results of accelerated life testing are presented to evaluate equalization requirements and to compare passive and active equalization approaches for valve-regulated lead-acid (VRLA) batteries. In both heavy cycling duty and high-temperature duty, battery degradation appears very early during expected life in the absence of equalization. The degree of equalization is critical: results show that voltage differences should be held to less than 15 mV/cell to prevent SOC separation in repeated cycling. The tests confirm that conventional overcharge-based passive equalization is effective for VRLA batteries—if there is sufficient time to ensure SOC matching among cells. Most proposed active voltage equalization methods in effect transfer the problem of SOC matching to external voltage matching of sensors and magnetic elements. Matching at the 15 mV/cell level is costly. A switched-capacitor approach has been identified that avoids this limitation. Test results show that switched-capacitor equalization is useful, particularly when the series string is too long to support enough time for passive equalization.

1. Introduction

Nearly all energy storage applications use series combinations of battery cells to meet voltage requirements. During recharge, each cell carries identical current, but the voltages might not balance. Sophisticated users have long been aware that series charging is associated with charge imbalance problems, although it is only recently that imbalance has been considered to be a major limiting factor in a wide range of applications. Valve-regulated lead-acid (VRLA) batteries are constructed with several design features to mitigate imbalance problems. A key feature is recombinant catalyst technology that recovers water as gas is produced during overcharge. When a catalyst is present, the amount of positive plate material must increase to allow oxygen to be generated in sufficient quantities to recombine with all the hydrogen [1]. Thus we can distinguish between passive approaches to balancing, in which gassing is allowed to occur, and active balancing, in which external circuits or power converters manage the charging of individual cells or monoblocks. In general, VRLA batteries are designed to support passive balancing — a forced overcharge equalization process, in which a deliberate overcharge is applied to the cells.

A major drawback of forced overcharge is the extreme inefficiency it creates in the charging process. In [2], the working profile of a typical uninterruptible power supply (UPS) battery is shown to be 95.5% overcharge, 4.49% normal recharge, and

0.01% discharge. Even under the most optimistic assumptions, such a profile implies that almost all the energy delivered to a UPS battery is intended to equalize it.

An effective equalization process will bring about a match among the state-of-charge (SOC) levels of cells in a series string. In the literature, cell voltage has been used as a surrogate for SOC in most proposed active equalization approaches. Several authors [3-8] have introduced various circuit-based voltage balancing techniques. Unfortunately, none of these papers has confirmed the relationship between voltage and SOC balance in the dynamic environment of an active equalizer. More importantly, published work does not confirm that external equalization methods offer battery life benefits. Previous studies of several active methods [4,6,7,9] all used large prearranged mismatches. For each case, the experimental work confirmed that the circuits were able to make the voltage differences smaller. However, such a test is not realistic. Practical equalizers would be asked to maintain tight match in a new battery pack rather than to restore match to a badly unbalanced pack. The mismatch levels would be measured in millivolts rather than volts.

2. Summary of Tests

The purpose of this paper is to consider equalization issues, and to make use of accelerated life tests and other operating tests of VRLA batteries as the basis for discussion of the issues and validation of results.

Two types of accelerated tests were used. In a fast cycling test, a moderate rate ($C/3$, where C is the nominal current) discharge and charge sequence was used repeatedly over several weeks. The ambient temperature was maintained at 22°C during the entire test. In an elevated temperature test, battery strings were held at a float potential in a 75°C ambient, and batteries were cycled once each week to evaluate capacity. Each test used strings of twelve Cyclon¹ brand VRLA single cells with a nominal capacity of 5 A-h at the $C/10$ rate. Eight sample strings were used for cycle testing and four strings were used for thermal testing—a total of 144 test cells.

A prototype hybrid electric vehicle [10] was used as a dynamic test bed for active equalization. The vehicle uses a series set of 26 Genesis¹ brand VRLA monoblocks rated at 16 A-h each. A hybrid vehicle application demands full power capacity from its batteries. When the car is in operation, the current is normally

¹Cyclon and Genesis are registered trademarks of Hawker Energy Products, Inc.

several times the C rate, whether during discharge as the vehicle drives or during charge as it brakes or obtains energy from the vehicle's engine-generator set. For passive equalization tests, an external charger that enforces both current and voltage limits was used. Active equalizers were installed and tested as well.

3. Is equalization necessary?

The need for equalization is understood among many users and manufacturers. Passive equalization is in place in almost all flooded lead-acid, VRLA, and nickel battery applications. The conventional approach is the same as that used in an automobile: provide a charger that can deliver up to a limit on the order of 2.3 V to 2.5 V per lead-acid cell. This is always well above the open-circuit voltage expected for a fully-charged cell, which is about 2.15 V at 25°C [11]. The extra voltage serves to overcome plate potentials and internal effects to drive the internal energy storage reactions to completion. Any excess voltage produces an energy loss—accepted as a cost of using a battery.

The basic necessity for equalization is confirmed experimentally in Fig. 1. This result reflects a repeated cycling test that began with fresh cells. In the repeated C/3 sequence, test packs 1 and 2 were charged to 2.45 V/cell with a cutoff of recharge when the current fell below C/100. Packs 3 and 4 were charged to 2.30 V/cell, again until the current fell below C/100. With the relatively high cutoff current, little time was allowed for any type of equalization in any of the packs. The performance is very poor. These cells fell below 80% of their initial capacity after only about 28 cycles. The manufacturer reports 400 cycles for this depth of discharge with proper passive equalization. The experimental result of less than 30 cycles is exactly consistent with the manufacturer's warning about undercharge [12].

3.1 How Accurate Must Equalization Be?

Static accuracy requirements for equalization can be inferred from Fig. 2, which represents open-circuit voltage as a function of state-of-charge for VRLA batteries similar to the Cyclon [13].

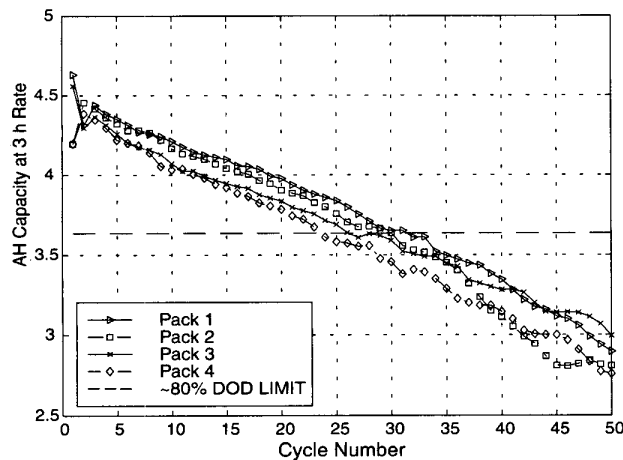


Figure 1: Capacity vs. Cycle Number Without Equalization.

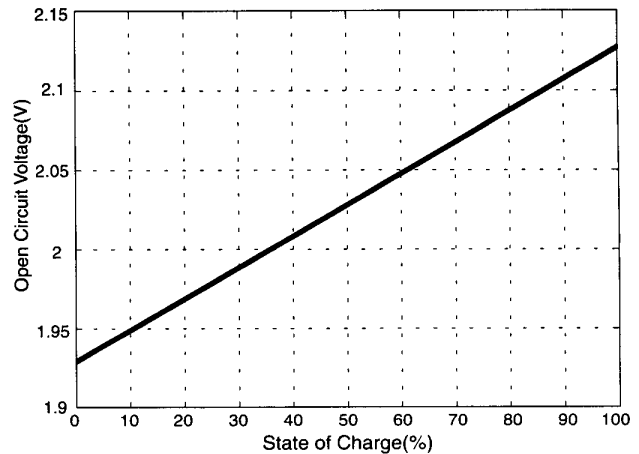


Figure 2: VRLA Open Circuit Voltage vs. State of Charge

The difference between 0% SOC and 100% SOC is 200 mV on the graph, which is based on a long resting interval between measurements. Even if Fig. 2 is considered the complete story, we notice that the voltage change is just 2 mV per percentage point SOC. It is immediately clear that steady-state voltage imbalance on the order of 20 mV implies SOC imbalance on the order of 10%. In dynamic situations, only a process able to achieve voltage imbalance well under 20 mV, working in the same manner among cells, will be useful for SOC equalization.

Actually, this result is a "best case" situation. To test dynamic accuracy requirements for equalization, the cycling test was repeated with fresh batteries and passive equalization. In this case, the charge voltage is again allowed to reach 2.45 V/cell, but the batteries were held at this level for 15 h to allow time for equalization. Fig. 3 shows the capacity history over repeated cycles, while Fig. 4 shows the average per cell voltage gradient. An external circuit attached to test pack 2 shunted part of the overcharge current to partially counter the action of passive equalization. The two packs track each other for about 15 cycles, at which point the

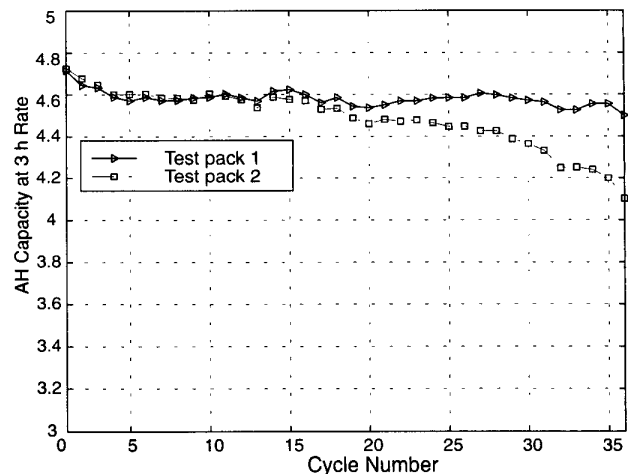


Figure 3: Capacity vs. Cycle Number, Passive Equalization.

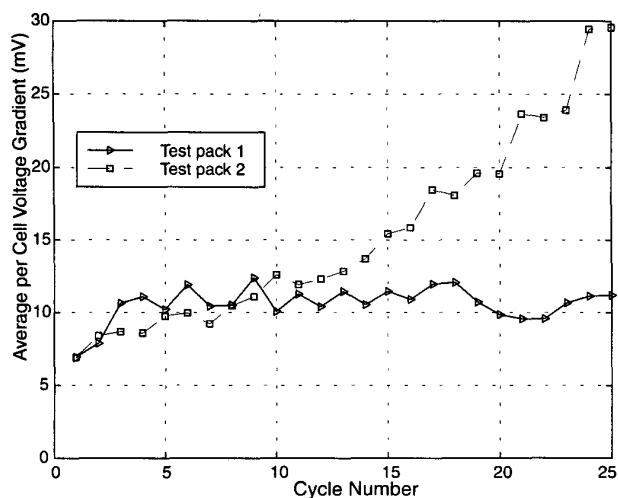


Figure 4: Average Voltage Gradient, Passive Equalization

average gradient in pack 2 rises above 15 mV/cell. After that time, total capacity begins to drop noticeably in the second pack, while the voltage gradient continues to rise. Test pack 1, in which passive equalization is allowed to proceed normally, shows much less significant loss of capacity, and exhibits a voltage gradient on the order of 12 mV/cell. The experimental evidence strongly suggests that 15 mV/cell is an upper bound for voltage-based equalization.

For temperature effects, the open-circuit voltage coefficient for lead-acid cells is about +0.2 mV/°C [14]. From an equalization perspective, this coefficient suggests that temperature gradients on the order of 10°C/cell will have little effect on SOC matching. Practical lifetime considerations also come into play. Manufacturers usually recommend a voltage correction for charging, with typical values of -2.5 mV/cell/°C [15]. On this basis, we expect that voltage matching targeted to 10 mV/cell would provide enough headroom to support an acceptable SOC match for temperature gradients up to at least 2°C/cell.

3.2 Passive Equalization Effectiveness

Notice that the test pack 1 results in Figs. 3 and 4 support the value of passive equalization. The tight matching in Fig. 4 confirms that the process leads to voltage equalization, while the slow drop-off in capacity in Fig. 3 represents near-nominal performance by these batteries. Fig. 5 recognizes a similar result for elevated temperature. In Fig. 5, the test has been conducted at 75°C. The float potential is dropped to 2.12 V for test pack 1 and 2.3 V for test pack 2. At 75°C, float life on the order of 8 to 16 weeks would be expected [16]. The figure shows about 10% capacity loss from the initial value after 6 weeks of testing, consistent with expectations. The overcharge voltage would appear to be adequate to maintain capacity over the (reduced) life.

Passive equalization is as much a matter of time as of voltage. For example, packs 1 and 2 in Fig. 1 show degradation even though the total voltage is driven to 2.45 V/cell. The degradation is caused

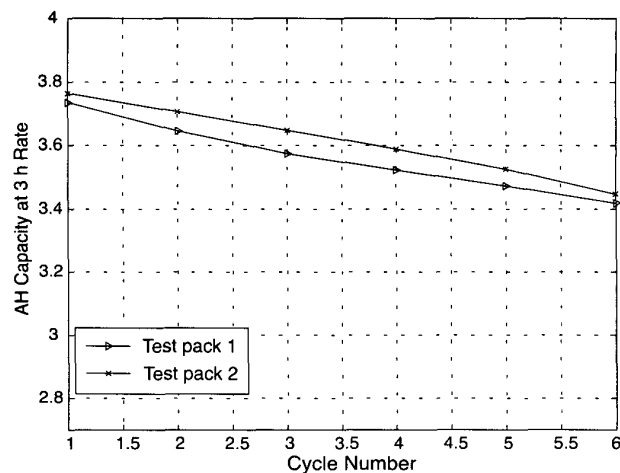


Figure 5: Capacity vs. Cycle Number, High Temperature Float Test.

by lack of time to bring each individual cell to a consistent average voltage. Some helpful results on this issue are given in [9]. In that work, passive equalization is supplemented with a firm voltage limit: charge voltage is always limited to keep the highest cell voltage below the target maximum. The total time to restore balance in the string in [9] extrapolates to approximately one week, but charge times of 12 h or less made imbalance worse. This is still a passive approach, but the enforcement of a local voltage limit prevents excessive loss and heating while other cells catch up.

Consider a string of 100 VRLA cells, with state-of-charge values randomly distributed between 95% and 100% and a charger in operation. As many of the cells begin to receive charge return in excess of 100%, the current drops quickly. In Cyclon cells, experimental results at 25°C show that the current drops below C/1000 within 24 hours even with a cell voltage as high as 2.45 V. Thus the highest cells in the string will limit the current quickly. With an average cell voltage of about 2.40 V imposed on the string, and given that a substantial fraction of the current will go into gassing or side reactions in cells at 95% SOC or more, a few weeks will be required to reach a 105% charge return target when 100 cells are in series. This expectation is borne out in Fig. 6, an experimental long-term charge on a series combination of two 12 V VRLA monoblocks taken from [17]. The batteries began with a small imbalance (about 10% SOC difference). The voltage difference drops by about 1 V over an interval of 60 h, which is consistent with an exponential decay time constant of 150h. Several weeks will be needed to restore balance in this small series configuration. In general, the longer the string the harder it will be to ensure sufficient voltage for an individual cell. Applications that combine high rates and high voltages, such as electric and hybrid vehicles, are likely to have considerable trouble with passive equalization. This problem has been reported in hybrid and electric vehicle prototypes [4,18].

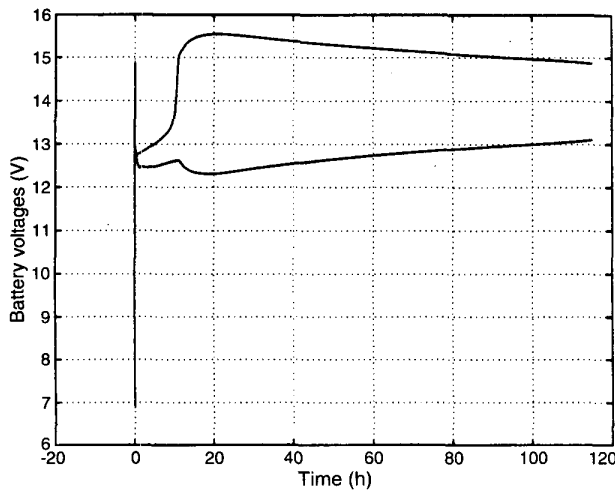


Figure 6: Voltages of Two Series 12 V Monoblocks, Passive Equalization.

4. Active Equalization

In active equalization, the objective is to transfer charge dynamically to low cells to facilitate equalization. Proposed versions have almost always considered voltage as the basis for a process, although it is possible that in the future conductance data or other SOC measures will be used in place of voltage. The existing active circuit methods for voltage equalization can be lumped into four major categories:

1. **Parallel charging.** In this arrangement [19], switches or relays reconfigure the battery pack. During discharge, a series connection is used. During charging, the pack is reorganized to place the smallest allowable units (cells or monoblocks) in parallel to assure equal voltage charging. A key drawback of this approach is that it is difficult to scale to large series strings. The switches must be able to handle full current ratings during both charge and discharge. The need to reconfigure requires a distinction between charge and discharge sequences that is inconvenient in many applications.

2. **Active shunting or lossy matching [19].** In this arrangement, a separate shunt circuit is provided for each monoblock. When the voltage exceeds a predetermined level, the shunt activates to divert current around the battery. The excess energy can be diverted through a resistor or other load. From a modelling perspective, the active shunting process acts like a zener diode in parallel with a battery. Although overcharge energy is lost in the shunt rather than being directed into a gassing process, active shunting does not reduce losses compared to forced overcharge techniques. A more fundamental limitation is that the degree of equalization depends on the degree to which individual shunt elements are matched. The balance problem is moved from the battery cells to the shunting devices.

3. **Full-string battery-by-battery power converter approaches.** Several power electronic techniques have been developed. One

example [8] is to replace a set of active shunts with a multi-port power converter, then redirect overcharge energy back to the main charger or to other batteries in the string. Other examples [4] use the inherent operation of multi-output forward or flyback converters, which deliver energy preferential to the lowest-voltage output. The practical challenge is to build converters with a sufficient degree of output matching [20]. This becomes increasingly difficult as the number of units to be equalized rises above two.

4. **Local equalization.** In these cases, a local circuit works to equalize two adjacent batteries or cells. The connection is modular, with each circuit associated with just two monoblocks or cells. Equalizers can be overlapped or synchronized to equalize a full string. Local equalizers can take the form of a buck-boost converter with voltage sensing and control [5], or can be accomplished with an open-loop switched capacitor circuit [6]. The latter approach leads to exact voltage balance without any sensing or control.

4.1 Accuracy Requirements

Recall the need for matching at 15 mV/cell or better. To address minor temperature differences and account for any other problems, active processes will need to be able to resolve and correct cell-by-cell differences on the order of 10 mV — under 0.5% on a 2.5 V scale, and less than 0.1% on a 12 V scale. Parallel charging avoids any problems here, but it is unwieldy. Most proposed active methods are intended for monoblocks, and so need to achieve accuracy levels of 0.1%. For any methods based on multiple output power converters or multi-port circuits, 0.1% accuracy requires trimming. Modern low-cost power converters cannot hold this level of accuracy over extended time intervals without frequent calibration. Even the passive-based method in [9] will suffer from this problem, since small errors in measurements will influence the voltage limit setting and the equalization process.

Local equalization methods fare better, since the cell-by-cell error levels are less extreme and because only two measurements are involved. In the local case, it is conceivable that a single measurement circuit could be arranged to measure local difference directly. A successful equalization approach should be sensitive only to voltage difference (with precision better than 10 mV), and ideally acts like a parallel charge/series discharge connection. The need for high precision certainly favors methods that extend well to cell-by-cell connection. Switched capacitor equalization [6, 21] is a local approach that has these characteristics. In the switched capacitor case, a single capacitor is switched rapidly between adjacent cells or monoblocks. The capacitor charges when connected to the higher-voltage cell and discharges when connected to the lower-voltage cell. A sample circuit is shown in Fig. 7. This simple process forces current to flow until adjacent voltages are exactly the same, without regard to values, without the need for any sensing, and with no accuracy requirements. It is well known that a capacitor switched between two ports can be treated like a linear resistor connecting the ports [22]. The switched capacitor

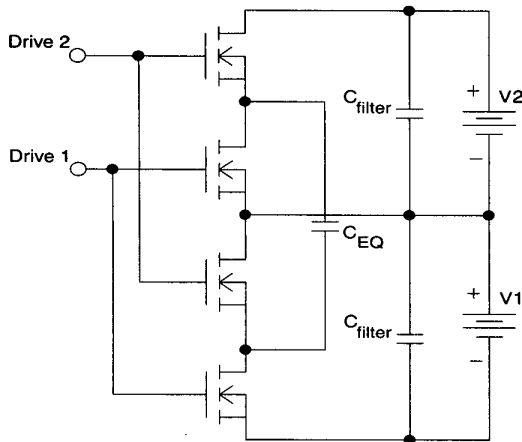


Figure 7: Switching Capacitor Battery Voltage Equalizer

equalizer acts as a virtual parallel connection of separate cells, with a resistance inversely proportional to the product of the switching frequency and the capacitance.

Local equalization methods extend to a long string by overlap of circuits between adjacent units. For n units, $n-1$ equalizers are used. The individual modules from Fig. 7 handle only the sum of voltages of the two local units and the interchange current. Bulk charging is supplied externally in the usual way, and thus acts independently of the equalization process. Local equalization has the important advantage that it is not a “top-off” process; equalization can be performed continuously without regard to charge, discharge, or SOC of the string. Switched capacitor equalization has additional advantages. Not only does the voltage difference become exactly zero in the limit, but the current also becomes exactly zero when the voltages match. This approach does not discharge the batteries in the long run by continuous low-level charge interchange, in contrast to [5]. It is also possible to synchronize switch operation to reduce the module number. In [21], a synchronization approach for the switched-capacitor method reduces the number of modules to $n/2 - 1$ instead of $n - 1$.

4.2 A Diffusion Model

In switched capacitor-based equalization, consider a situation with an equivalent resistance given by

$$R_{eq} = 1/(f_{switch} C_{EQ}) + R_{min} \quad (1)$$

where $f_{switch} C_{EQ}$ is the ideal result for a switched capacitor circuit and R_{min} is the actual minimum resistance determined by connection values, capacitor equivalent series resistance (ESR), resistance in the switches, and so on. The current between two adjacent units n and $n+1$ is given by

$$i_n = \frac{v_n - v_{n+1}}{R_{eq}} \quad (2)$$

Ideally for m cells, the net current flow would be

$$i_{n,m} = \frac{v_n - v_{n+1}}{m R_{eq}} \quad (3)$$

In the limit of small differences, the current becomes

$$i = -1/R_{eq} dv/dn \quad (4)$$

which is a diffusion relationship. In addition, some portion of the charge serves to increase the cell state of charge. For the purposes of mathematical analysis, this change in energy storage can be treated as an equivalent internal capacitance model, C_{int} . The time rate of change of SOC, $dSOC/dt$, is a fraction of the cell current. Let $dSOC/dt = \kappa i$. The change in this value between cells, di/dn , is proportional to the time rate of change of voltage,

$$di/dn = C_{int} dv/dt \quad (5)$$

Equations (4) and (5) can be combined to produce a classical diffusion equation for cell voltage,

$$\frac{d^2v}{dn^2} = \frac{1}{k} \frac{dv}{dt} \quad (6)$$

with $k = \kappa/(R_{eq} C_{int})$. The solutions of (6) are well known [23], and the gradient will decay with a time constant proportional to $1/k$ and to the square of the number of cells. Intuitively, this makes sense. In a long string of cells, charge transfer among nonadjacent cells must step through all intermediate equalizers. Although the diffusion relation in (6) is straightforward to establish for switched-capacitor equalization or other local equalizers, the diffusion effect applies to most types of equalization. Since charge redistribution depends on voltage gradient in each method, the rate of change of local SOC is proportional to local gradient. This model supports the notion that long strings require much longer equalization times than short strings. At least one manufacturer [24] recommends against series charging of VRLA strings above nominal voltages of 24 V.

4.3 Switched Capacitor Equalizer Design and Operation

For switched capacitor equalizers, the design requirements to support useful equalization are straightforward to establish. For example, if interchange current of $C/1000$ is desired with a voltage difference of 10 mV between 5 A-h single VRLA cells, a connection resistance of $10 \text{ mV}/5 \text{ mA} = 2 \Omega$ or less is required. Consider an equalizer like that of Fig. 7, with $R_{min} = 0.5 \Omega$. To achieve 2Ω of equivalent parallel connection resistance, the design requirement is

$$\frac{1}{f_{switch} C_{EQ}} < 1.5 \Omega \quad (7)$$

For a switching frequency of 20 kHz, this requires $C_{EQ} > 33.3 \mu\text{F}$. A design such as the one in Fig. 7 will readily achieve practical targets with capacitance values on the order of 100 μF and switching frequencies in the range of 10-50 kHz. Notice that C_{EQ} values below about 10 μF will not be very useful for 5 A-h cells. If a more accelerated equalization process is needed with an interchange current on the order of $C/100$, an equivalent resistance of 0.2Ω is

required. This could be difficult to achieve because of realistic limitations on R_{min} . In general, rates between $C/500$ and $C/2000$ can be produced even at voltage differences of only 10 mV/cell. Any equalization process in a long string will be slow, but this is a less significant concern with a switched capacitor method. A switched capacitor process can be applied continuously in the background, since the interchange current becomes zero when the voltages match. There is no undesired leakage current or loss, and the only energy overhead is the power required to operate the switches. In a practical design, the energy overhead can be made lower than the self-discharge energy of the cells, at which point there is merit to incorporating continuous equalization into the cell construction.

To test switched-capacitor equalization, a set of modules was developed for a string of 26 VRLA monoblocks with nominal voltage of 12 V each. The capacitance values are 220 μ F per module, with a switching frequency of 15 kHz. The batteries are Genesis 16 A-h VRLA units. In Fig. 8, the voltage profile is shown over an interval of 24 h. The equalizers are functioning during a charge, with an overall limit of 359 V (2.30 V/cell). The general shape of the profile is preserved as it decays toward a constant average level, as would be expected for a diffusion process. Are the active equalizers performing this function? To test this, the capacitor was removed from one module. Fig. 9 shows the voltage profile several hours after the change, and again after a two-week rest interval and an overnight equalization session. The abrupt change between monoblocks 6 and 7 shows the location of the missing capacitor. The missing device acts as a block — preventing the active equalizers from exchanging charge among the two sets.

Fig. 9 is compelling evidence that these active equalizers have a much stronger effect than passive equalization, at least for target cell voltages of 2.30 V/cell. The voltage cannot be set lower than this to avoid corrosion effects that would diminish lifetime [16, 25]. The repeated cycling test was used to help determine whether active equalization can substitute for passive equalization. In this portion of the testing, two packs were discharged at the $C/3$ rate, then recharged at a similar rate up to an average value

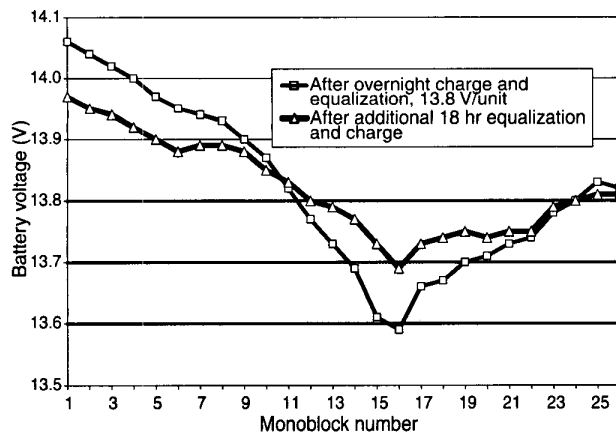


Figure 8: Equalization Attempt, Fully Functional Units

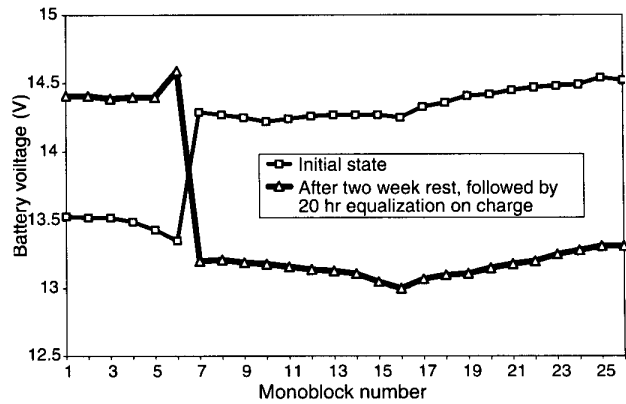


Figure 9: Equalization Attempt, Capacitor Removed from One Rnit

of 2.30 V/cell. The packs were held at this voltage for 15 h before the next discharge. Results are shown in Figs. 10 and 11. Pack 1 has no equalization (since the voltage is too low for effective passive equalization), while pack 2 uses switched-capacitor equalizers with an equivalent resistance of about 8 Ω . In Fig. 11, the unequalized pack shows a voltage gradient of more than 15 mV/cell almost immediately, and the value continues to rise. Lifetime is adversely affected, with only 20 cycles achieved before the capacity fell below 80%. The active equalizers in this example have too much impedance to move sufficient current. Although the voltage gradient is brought to much lower values than for pack 1, the gradient still exceeds 15 mV/cell at all times, and the lifetime degradation is the same as for the unequalized pack. The interchange current, which is less than $C/2500$ with a 15 mV difference, is not enough to restore balance. This confirms that an equalization process that cannot transfer useful current levels with small voltage differences will not do the job.

4.4 Lifetime Extension

Can active equalization help with lifetime extension? The results so far establish a necessary condition for this objective:

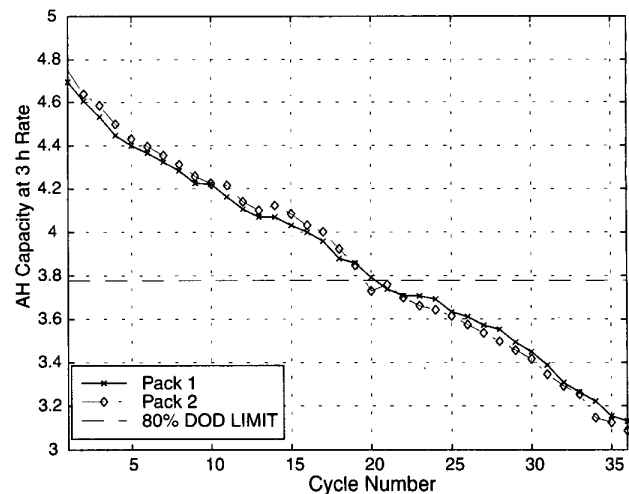


Figure 10: Capacity vs. Cycle Number Without Passive Equalization

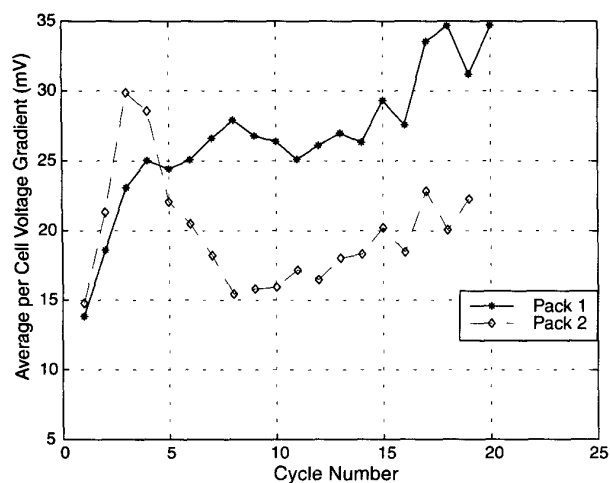


Figure 11: Voltage Gradient vs. Cycle Number

equalization must exchange significant current levels for cell-to-cell voltage differences of 15 mV or less. Is this sufficient to extend cycle life? Fig. 12 shows grid corrosion acceleration in a VRLA cell as a function of the plate polarization, taken from [25]. The minimum of 80 mV polarization corresponds to a cell voltage of 2.23 V, which closely matches the 2.27 V float voltage recommended for Cyclon cells [11]. While it is plausible that a float charge process supplemented by active equalization would extend life, this is not consistent with the results in Fig. 5, which did not show lifetime improvement with lower voltage in the high-temperature float test.

The strongest conclusion that can be drawn is that present VRLA designs are predicated on passive equalization. Active equalization brings a new set of constraints, and it is likely that a VRLA design predicated on active equalization could achieve longer life. The results in [26] show that alternative charging procedures can extend life. Active equalization reduces the need for lossy charging procedures aimed at balancing a pack.

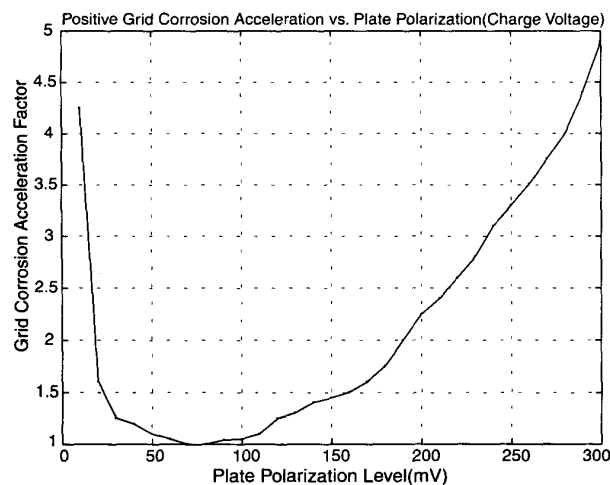


Figure 12: Charge Voltage Effects on Cell Corrosion

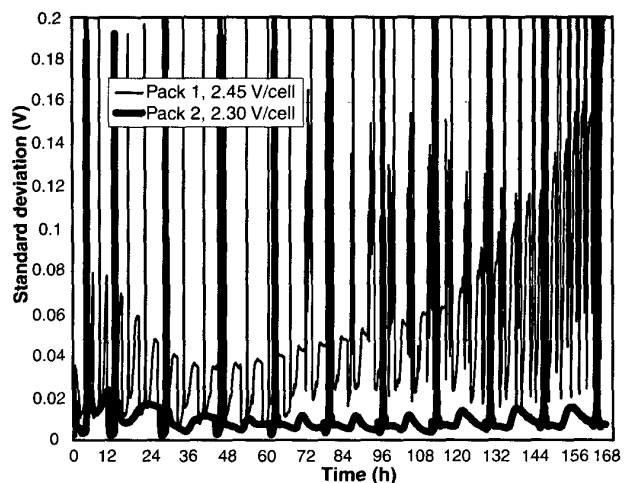


Figure 13: Voltage Standard Deviations of Cells.

With the design emphasis on passive equalization in modern VRLA batteries, it is difficult to predict possible life extension with other equalization approaches. An early result in [27] shows cycle life extension of 15% for a repeated C/3 cycle with switched capacitor equalizers. To test life extension effects generically, switched-capacitor equalizers were studied with conventional flooded lead-acid cells. The fast cycling tests were repeated with 5A-h flooded cells, wired individually to equalizer modules. One set of cells used purely passive equalization, with a voltage limit of 2.45 V/cell. A second set used a limit of 2.30 V/cell and was supplemented by active equalization. Fig. 13 shows the standard deviation of the twelve cell voltages during the test. The glitches occur when the current changes from charge to discharge to begin each cycle. The pack 1 results (charging at 2.45 V/cell) show the cell voltage standard deviation falling below 40 mV after about seven cycles, but then the variation begins to climb. After about 100 h, water loss became significant, and performance began to degrade. The pack 2 results (charging at 2.30 V/cell) show much better behavior with the active equalizers. The standard deviation falls below 10 mV after about three cycles. More important, the dynamic behavior of equalization can be seen during each charge cycle: after an externally imposed change, the active equalizers work to reduce the deviation and restore balance. For example, at a time of 86 h, the charging process began. The deviation jumped to 10 mV, but was brought down to less than 5 mV over the charge interval of about 6 h.

In Fig. 13, the equalizers are performing as intended, and are able to give useful results for voltage differences on the order of 10 mV or less. Table 1 shows measured water loss in the series strings. The large difference represents a real lifetime difference since the active equalizers are used to support charging at a lower voltage. The total water capacity of these batteries is about 500 g. VRLA battery catalysts cause much less water loss, but a charging approach that cuts loss by more than a factor of two would certainly be expected to extend cycle life by at least a similar factor.

Table 1. Water Loss for Flooded Batteries in Fast Cycle Test.

| Pack 1 | Pack 2 |
|--------|--------|
| 300 g | 171 g |

5. Conclusion

Equalization of VRLA cells is necessary for successful battery usage in many applications, especially high rate uses such as hybrid and electric vehicles. Equalization can be accomplished with voltage matching, but only if matching accuracy is better than 15 mV/cell. Passive equalization (forced overcharge) works if cells are exposed to an overcharge condition for sufficient time. In the accelerated life tests here, a time of 15 h at high potential was able to prevent SOC mismatch. Equalization processes can be modelled as a diffusion of charge, and the time required increases with the number of series cells.

One known method, switched capacitor equalization, achieves ideal cell-to-cell matching with a modular structure that can be extended either to monoblocks or individual cells. This equalization method can be designed to have a much stronger effect than passive equalization. Mismatch reduction was illustrated in a hybrid vehicle application. In [27], and also with a flooded lead-acid test, switched capacitor equalization provided substantial cycle life improvements. The application of precise active equalization in VRLA batteries brings with it new sets of design constraints. It is likely that VRLA designs that rely on active equalization will achieve longer cycle life than present designs optimized for passive equalization.

6. Acknowledgments

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7. References

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