Proc. IEEE INTELEC, 2005

Lifetime Effects of Voltage and Voltage Imbalance on VRLA Batteries in Cable TV Network Power

Brian Kuhn
SmartSpark Energy Systems
Champaign, Illinois, USA

René Spée
Alpha Technologies
Bellingham, WA, USA

Philip T. Krein
University of Illinois
Urbana, Illinois, USA

Abstract

Charge balance is known to be an essential consideration in series valve-regulated lead-acid (VRLA) battery applications. Conventional applications use passive equalization to maintain balance: periodic overcharge sequences. Active equalization uses external circuits to enforce charge balance without the need for overcharge. There is little published data to show the potential value of active equalization in float applications such as those common in telecommunications. Measured voltage balance data for a population of 2538 batteries in a set of 846 series strings are reported. Batteries showed a clear pattern of degraded life for charge voltages that differ by more than about ±0.1 V from an optimum charge voltage chosen to minimize positive grid corrosion. Passive equalization was able to keep about 63% of the batteries in the population within this range. The remaining 37% showed life degradation in a direct relationship to the charge voltage error. It is estimated that active equalizers capable of balance at the level of about 15 mV/cell would have maintained all the batteries near enough to the optimum range to avoid life degradation. An economic analysis suggests that active equalization would reduce tangible battery and associated maintenance costs by 31-36%. There would be additional economic benefits that are more difficult to quantify.

1 Introduction

State-of-charge (SOC) balance is important to maintain long-term life in series strings of all types of rechargeable batteries. The issues are well known for valve regulated lead-acid (VRLA) batteries. In the literature, it has been established that voltage balance is a suitable surrogate for SOC balance [1,2]. It has also been established that voltage imbalance gradients need to be less than about 15 mV/cell to avoid life degradation [2]. A major issue is that although a baseline threshold for the voltage gradient has been established, there are little or no data demonstrating the value of low gradients. Some questions that need to be answered include: How much is life degraded as imbalance increases? How does a 15 mV/cell target, obtained in a laboratory, reflect on actual usage of batteries? Do low gradients yield long life?

In addition to charge balance, the absolute charge voltage is a critical parameter. When voltage can be held close to the optimum float value for a given temperature, corrosion effects are minimized and lifetime is maximized. The potential benefits of equalization can be compromised by incorrect charge voltage or inaccurate temperature compensation.

A wide range of low-loss methods for equalization has been proposed [1,3-8]. All of these techniques are designed to move charge from one battery cell to another to perform equalization. The techniques vary in their complexity, with some requiring transformers [3, 6], microprocessors [6, 8], and semiconductors with a full battery system voltage rating (instead of a cell or monoblock rating) [1, 8]. Modular methods were introduced in [4], which applies buck-boost converters between adjacent cells or monoblocks, and [5], which applies switched capacitor methods. The modular approach in [10] is related to a forward converter topology as discussed in [3]. All of the techniques except [5] require measurement of cell voltages, and many only work while the battery is charging [1, 7, 8].

The purpose of this paper is to determine what equalization might be able to accomplish in terms of battery life extension in float applications. There have been very few studies that confirm the benefits of any equalization approach, or that establish the value of equalization in field use. A 20-cycle test in [2] showed that water loss was cut nearly in half for flooded lead-acid batteries with equalizers compared to those without. Actual street tests of a fleet of electric vehicles showed modest cycle life extension from equalization, in the range of 15-30% for those devices that worked [9]. Tests in [10] show much more significant improvement – a factor of about 3 cycle life extension in an aggressive hybrid electric vehicle test sequence. Other long terms tests [11] have been less conclusive.

The above studies address cycling applications. During cycling, impedance mismatches and other small differences among cells would be expected to produce differential charging. It is reassuring that cycling tests in [10] show that equalization extends the cycle life of a series string to that of the individual elements. It is expected that effective equalization will provide this level of performance when designed into a cycling application. The benefits in float applications such as telecom power systems are less obvious. Imbalance in float applications probably comes about because of mismatches in self-discharge characteristics or temperature gradients across a battery pack. It is important to study how equalization is likely to impact float situations.

2 Field Test Data

Needs for and possible benefits of equalization are explored here through field testing of a large population of VRLA batteries in a telecommunications float application. These field data quantify the lifetime effects of voltage imbalance or error. A sample of 846 battery strings in a cable TV system in a U.S. upper Midwest location, each constructed from three matched 12 V monoblocks [12] in series, was monitored after a service life of approximately 2 years to establish operating life performance. These batteries are maintained on float with a proprietary CATV power supply [13]. The target charge voltage is selected based on previous results to minimize positive grid corrosion. The voltage is temperature compensated in accordance with well-established practice. A typical power supply system for an outdoor CATV plant is illustrated in Figure 1.

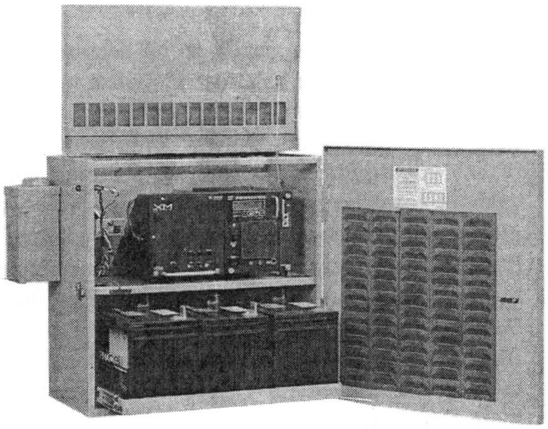

Fig. 1. Open enclosure showing batteries and CATV power supply with integral battery charger.

Installations of these types must meet increasing levels of performance. As voice-over-internet-protocol (VOIP) is being introduced in many cable systems, battery life and performance should tailored to achieve the lifeline power backup performance expected today from conventional wire telephony. For example, in a long-term outage in the plant, the CATV provider expects a certain run time, which in general is predicted based on equalized batteries. The unit in Fig. 1 protects its monoblocks with a low voltage disconnect, set to 10.5 V on the lowest battery. For mismatched strings, the discharge time can be reduced substantially and significant run time can be lost.

In these installations, a short-term overvoltage equalization charge is provided at regular intervals. This represents a “passive equalization” process as defined in [2]. The net effect is that these data represent a “best case” field test of 36 V battery strings in float applications. They use the best available conventional charging process, and do not apply any external balancing process.

It is noted in [14] that poor charging is the primary cause for short battery life. Lead acid batteries obtain their maximum lifetime if they are charged at the proper voltage, which needs to be temperature compensated. Excessive overcharging leads to positive grid corrosion and active material shedding – leading to a shorter cell life. Overcharging also leads to excessive gassing which can dry out the cell and cause other problems if the battery is not maintained properly. On the other side, overdischarging a cell is bad also, since it can reduce the electrolyte concentration low enough to damage the pore structure of the battery. Additionally, if the battery is stored in a discharged state, sulfation can occur on the negative plate, leading to decreased capacity and life of the battery.

It is apparent that it is important to maintain the battery at a proper voltage to obtain maximum life. With active equalization, it is possible to control the voltage of individual monoblocks or cells and prevent them from drifting apart. Without equalization, with a charge process based on the full stack voltage, it is possible that one of the cells will be overcharged (and damaged) during the charge process, while the other cells do not obtain full charge. Similarly during discharge, one cell may be overdischarged and damaged while the others have not yet been fully drained. Systems which monitor individual monoblock voltages during discharge will not deliver full capacity, since the lowest voltage battery dictates the end of discharge.

The test discussed here is based solely on passive equalization: overcharge at regular intervals. Data were recorded with resolution of 100 mV per monoblock. With 846 strings, there are 2538 different monoblock voltages in the data sample. The data are summarized in Table 1. The voltage differences are sorted into 100 mV bins, relative to the optimum. The number of units and percentage of units in each bin are listed. The measured availability reflects the average operating result in each bin, and the expected life is a bin average based on expected corrosion. The temperature differences are then normalized to the equivalent life that would have been expected at 25°C. These batteries are rated for eight years under such conditions. The acceleration factor is computed as eight years divided by the equivalent life for each bin – thus a 1 yr equivalent life would yield an acceleration factor of eight.

Table 1. Results for 2538 monoblock population.

Voltage difference	Number of units	Percent of total	Measured availability	Expected life, ambient	Equivalent life, 25°C	Accelera-tion factor
-0.8 V	42	2%	30.0%	1.9 yr	2.4	3.3
-0.7	14	1%	40.0%	2.5	3.2	2.5
-0.6	9	0%	49.0%	3.1	3.92	2.0
-0.5	37	1%	58.0%	3.7	4.64	1.7
-0.4	42	2%	70.0%	4.4	5.6	1.4
-0.3	96	4%	80.0%	5.1	6.4	1.3
-0.2	207	8%	90.0%	5.7	7.2	1.1
-0.1	779	31%	98.0%	6.2	7.84	1.0
0	55	2%	100.0%	6.3	8	1.0
0.1	776	31%	99.0%	6.3	7.92	1.0
0.2	244	10%	97.0%	6.2	7.76	1.0
0.3	99	4%	94.0%	6.0	7.52	1.1
0.4	44	2%	75.0%	4.8	6	1.3
0.5	19	1%	31.0%	2.0	2.48	3.2
0.6	19	1%	22.0%	1.4	1.76	4.5
0.7	8	0%	15.0%	1.0	1.2	6.7
0.8	18	1%	10.0%	0.6	0.8	10.0
0.9	6	0%	7.0%	0.4	0.56	14.3
1	4	0%	3.5%	0.2	0.28	28.6
1.1	20	1%	3.0%	0.2	0.24	33.3

The expected life was calculated based on average measured ambient temperature (using monthly highs and lows for the given geographic location), corrected for the known enclosure temperature rise.

These data, although they are a summary from a massive data set, only represent a snap shot. The information does not indicate when each string was last subjected to passive equalization, nor whether there is a particular trend. The battery population at the time the data were taken was approximately 2 years old. Given that the typical life time is around 6 years in this environment, a further degradation over the ensuing years is likely critical and would further deteriorate plant life. Alpha and most other manufacturers recommend that the batteries be commissioned as a balanced, matched set in a series string. Without this practice, the unbalance would be expected to be more significant.

3 Data Interpretation

Fig. 2 shows the histogram of voltage differences in Table 1. While only 55 units showed the desired voltage at the end, a total of 1555 were within ±100 mV of the ideal. This indicates that 63.4% of the batteries were maintained close to the desired voltage. A deviation of ±100 mV per monoblock can be interpreted as an average of ±16.7 mV/cell – not far from the 15 mV target level reported in [2].

Fig. 3 shows the equivalent lifetimes experienced for the monoblocks in the test, as a function of end-of-life voltage difference relative to the target. The results show an approximate linear drop in life for low voltages. For higher voltages, the effects are more complicated. Monoblocks maintained less than 0.3 V above the target experience less than 10% life reduction. Then life drops abruptly when the voltage rises to 0.4 V above the target.

Since the target voltage was selected on the basis of minimum positive grid corrosion, it can be hypothesized that the effects in Fig. 3 represent corrosion impacts within a monoblock. Fig. 4 presents acceleration factors listed in Table 1. Above 0.4 V, corrosion accelerates dramatically. Voltages below the optimum have a more gradual effect, but still accelerate the damage. A key aspect of Fig. 4 is that it confirms the target voltage: the optimum voltage based on corrosion predictions is also the optimum voltage for life in this float application. The accelera-

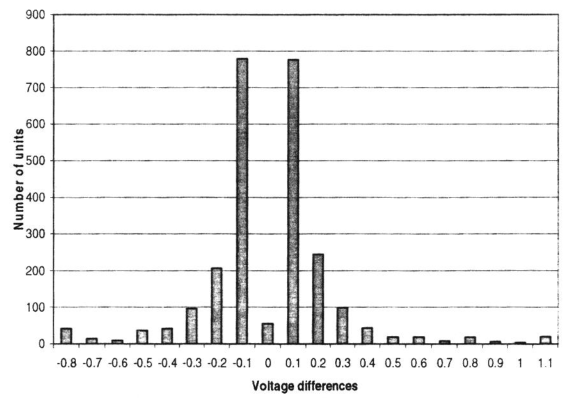

Fig. 2. Histogram of end-of-life voltage differences relative to target.

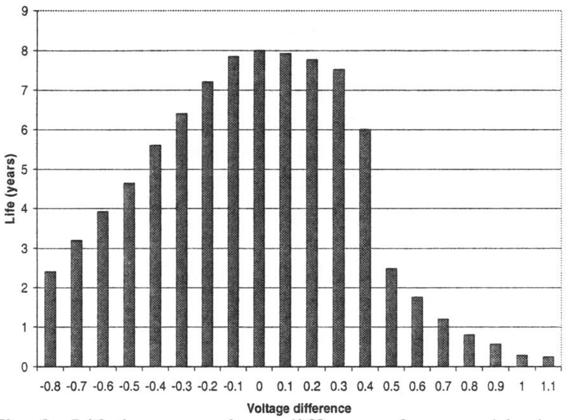

Fig. 3. Lifetime vs. voltage difference for monoblock samples (corrected to T=25°C).

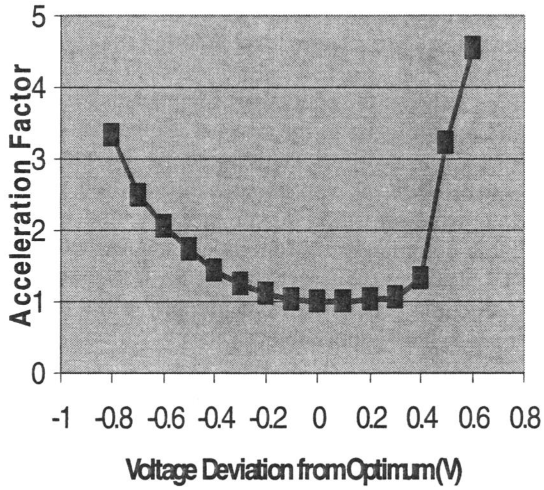

Fig. 4. Lifetime degradation acceleration factor vs. voltage difference.

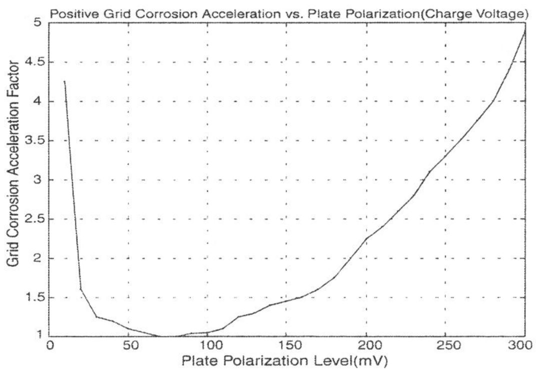

Fig. 5. Charge voltage effects on grid corrosion, from [16].

tion curve in Fig. 4 is based on J.J. Lander's research into polarization aspects related to lead-acid storage cells at the U.S. Naval Research Laboratory in the 1950's, which leads to the summary in [15]. Fig. 5, taken from [15], is provided here to show expected corrosion acceleration at the grid as the voltage differs from the ideal value. The results in Fig. 4 have been verified separately for the silver alloy gel chemistry used here [16]. More discussion of Lander's work and the implications in equalization for float charging can be found in [17].

According to Fig. 4, battery life drops by about 20% when the monoblock voltage differs from the optimum by about 0.3 V. On a per-cell basis, this corresponds to 50 mV. Cell-by-cell errors at this level have significant impact on life, and translate immediately into extra system cost. By the time the monoblock error reaches 0.5 V, life is cut in half. From an engineering perspective, cell-by-cell errors in the range of 15 mV have little impact on life.

The results in Fig. 3 can be interpreted in terms of both charge voltage selection and equalization for VRLA packs. On the basis of 12 V monoblocks, the external charger should be set within 100 mV of the optimum total potential. If block-by-block equalizers are in place and are designed to limit the voltage gradients to less than 15 mV/cell, then each monoblock would be expected to be held within ±100 mV of the optimum potential. Under these conditions, maximum life should be achieved in accordance with Figs. 3 and 4. This is a significant result: provided the overall charging strategy is set correctly, equalization will insure the benefits of minimum corrosion, and maximum lifetime will be possible.

4 Cost and Benefit Discussion

The overall data can be interpreted in more detail on a cost benefit basis. Consider that in this case, more than 63% of the monoblocks were maintained successfully with a passive equalization process, and many of the other monoblocks had relatively limited life degradation. Indeed, the data in Table 1 suggest that 88.9% of these monoblocks experience less than 20% life reduction. Table 2 lists expected plant-years, the product of number of monoblocks times expected years of life from Table 1, and the plant-year product that would be observed if an active equalization process were able to maintain proper potential. For cells near the optimum, the improvement is small. The total improvement expected for the entire population is 15,960 plant-years, compared to 14,600 experienced – a 9.3% increase.

This interpretation is based on a snap shot after a service life of two years. In a real installation, further degradation in balance would be expected in later years. The data in many senses represent *best case* results for a passive equalization method optimized for charge voltage. The measured 9.3% increase in service life should be relatively conservative.

Table 2. Plant-years expected for passive and active equalization.

Voltage difference	Number of units	Expected plant-years, passive balance	Expected plant-years, active balance
-0.8 V	42	80.0	264.0
-0.7	14	35.6	88.0
-0.6	9	28.0	56.6
-0.5	37	136.3	232.6
-0.4	42	186.7	264.0
-0.3	96	487.6	603.4
-0.2	207	1182.9	1301.2
-0.1	779	4847.3	4896.7
0	55	349.2	345.7
0.1	776	4877.9	4877.9
0.2	244	1502.8	1533.8
0.3	99	590.9	622.3
0.4	44	209.5	276.6
0.5	19	37.4	119.4
0.6	19	26.5	119.4
0.7	8	7.6	50.3
0.8	18	11.4	113.1
0.9	6	2.7	37.7
1	4	0.9	25.1
1.1	20	3.8	125.7

While an increase in total battery life for the entire population of only 9.3% may seem to have limited benefit, the real advantage comes about in terms of predictive maintenance scheduling and in predictable performance. With passive equalization, more than 36% of the batteries were failing prematurely, i.e. had a voltage unbalance of more than 100mV per monoblock. Some of these batteries are shown to have a very reduced life span compared to their design life. An on-demand replacement process is required, with expensive truck rolls each time a monoblock begins to fail. Active equalization is likely to relieve this. In this population, it could be possible to set up fixed 6 yr replacement cycles with active equalization in place. This could save most of the on-demand truck rolls, and thus could reduce intervention maintenance costs substantially. In a large telecom power network, the cost savings are compelling.

In VOIP and other high-performance applications, active equalization should support predictable run-time during a power loss situation, since discharge time will not be dominated by a single weak monoblock. This effect allows battery strings to be sized more precisely based on the installation requirements.

The economics can be considered in more details. In an actively equalized system, a fixed six-year replacement cycle can be applied. In this study, a total of 585 batteries lasted less than six years (those with imbalances outside the range of -0.2 V to +0.4 V). A truck roll costs approximately as much as a battery in routine circumstances (but much more if the location requires special access considerations. The original investment of 2538 batteries is not only extended by 9.3%, but the additional savings in truck rolls translate into further savings of about 22%. For these three-battery strings, active equalization delivers cost savings of 31-36%. Uniform known run-time adds an extra soft economic benefit that is harder to quantify, although discussions about VOIP lifeline requirements are likely to make this advantage increasingly important.

This analysis also does not account for the fact that with active balancing, in case of an early life failure (for example due to a manufacturing defect), only the failed battery needs to be replaced rather than (as is recommended today) the entire string. Moreover, the matching requirement at the time of commissioning is eliminated, saving time, labor and money.

5 Conclusion

Equalization of series battery strings is essential in float applications such as telecommunications power systems. The passive equalization process commonly used today was tested with field measurements in a CATV system. Results showed that about 63% of batteries were maintained effectively over the measurement interval by means of passive equalization. The results also validate positive grid corrosion as a basis for optimum charge voltage. Lifetime reduces directly as voltage error increases from the optimum value.

The 36% of batteries that were not held in balance by passive equalization could have been addressed with an effective active process. Based on the results, an active equalization process capable of balancing VRLA batteries to within about 15 mV/cell would be expected to deliver the benefits of optimum charge voltage to a population of batteries. Initial economic analysis shows expected battery and maintenance cost savings of at least 30%. Less quantifiable factors suggest that actual savings will be substantially higher.

In the future, we hope to continue the data monitoring process to further evaluate lifetime performance and effects in VRLA units by monitoring a large deployed base over time using the power supply status monitoring system.

6 Literature

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