Life Extension Through Charge Equalization of Lead-Acid Batteries

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Abstract—**Charge equalization is an important part of the charge process for series-connected battery cells. This paper reviews battery behavior and performance related to the equalization problem, in the context of vavle-regulated lead-acid batteries. As established in prior work, equalization precision on the order of 10 mV/cell is required for a successful process. Equalization processes that can achieve this precision do indeed extend the life of battery packs. Active equalization speeds the process and supports exchange of a single failed cell or monoblock Passive equalization (conventional overcharge) is too slow in most contexts for strings longer than about 12 cells. Active equalization provides clear life advantages over other approaches. The results are consistent with the hypothesis that a properly designed active equalization process can provide battery cycle life for a series string that matches the cycle operating results for an individual cell.**

Index Terms— **Battery equalization, charge equalization, battery management, charge balancing**

I. INTRODUCTION

Batteries are nearly always used in series combinations of multiple cells. When a series string of cells is charged as a group, a single current is imposed on all the cells. However, if the voltages begin to differ, the result is a charge imbalance that can lead ultimately to battery failure. In any useful series battery charge process, some type of "charge balancing" or "equalization" must take place to restore balance or at least prevent it from growing.

The need for equalization is well established. In most conventional battery charging practice, equalization is addressed either by driving the charge to a sufficient potential to assure some degree of overcharge for all cells, or with a separate higher-voltage charging step intended to reach the weakest cells. In recent years, electric and hybrid vehicle applications, which tend to use very long series strings and which push battery performance to extremes, have brought charge equalization into wider view. In [1], results with lead-acid battery packs in the General Motors EV1 production electric car are presented. The paper focuses most of its attention on the charge equalization problem. In [2], a team from Optima Battery (now part of Johnson Controls) reports

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that "Pack imbalance is perhaps the most serious issue with large series string packs."

Although much of the research with respect to equalization has considered long series strings (100 or more cells in series), problems of equalization extend down to short strings of just a few cells. In [3], a conventional block of six lead-acid cells was tested with a voltage-limited charge process, in which the maximum charge potential is held below 2.35 V for any individual cell. When a 12-hour charge was used in this case, performance degraded from cycle to cycle. Only when the charge process was extended to 16 hr was there enough time for equalization to bring about recovery. Even then, approximately one week would have been needed to fully restore charge balance. The equalization process represented by this charge strategy reflects a "passive equalization" approach: ensure that strong cells are subjected to overcharge (limited by voltage in [3]) until weak cells regain full charge. The process is slow even for familiar 12 V monoblocks.

Several key questions must be considered with respect to equalization:

1. Many equalization processes match cell voltages. The real need is to match cell state-of-charge (SOC). Is voltage an accurate surrogate for SOC?

2. How accurately must the cells be matched to make the process useful?

3. What are the benefits of equalization?

4. Will equalization extend battery life and reduce costs? These questions are addressed in this paper, primarily in the context of modern valve-regulated lead-acid (VRLA) batteries.

II. VOLTAGE BALANCING

An equalization process is intended to match the SOC among cells in a string. Since the charge current matches in a series string, the implication is that voltage should match. However, the relationship between voltage and SOC is not necessarily trivial. Fig. 1 shows a graph (from [4]) of cell voltage vs. SOC for a lead-acid cell. The relationship is based on measuring open-circuit voltage after about 30 min of rest. It shows a simple linear relationship. The total voltage change over a 0 to 100% SOC change is about 0.2 V, corresponding to 2 mV for every 1% change in SOC. Two key inferences can be made from this graph:

1. For lead-acid cells in steady state, voltage provides useful information about SOC.

2. Cell-to-cell voltage matching on the order of 10 mV corresponds (in steady state) to SOC match on the order of 5%.
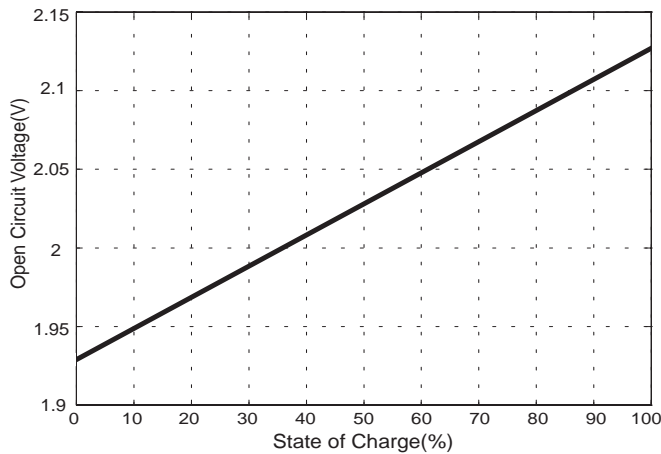

Fig. 1. VRLA open-circuit voltage vs. state of charge (from [4]).

It is a challenge to interpret this behavior under dynamic conditions. A reasonable assumption is that low currents will reflect similar behavior, although high currents will distort the voltage behavior and could lead to erroneous results. Experimental life tests have been conducted to evaluate the voltage-matching behavior of VRLA batteries under dynamic conditions. Figs. 2 and 3 (from [5]) illustrate the results. The figures present test results for two 12-cell VRLA strings tested with and without an effective equalization process. With equalization in action (Test pack 1), the cell-to-cell variation is held to about 12 mV. Without equalization, the variation begins to drift up after about 13 cycles. Fig. 3 shows the effect on performance. The string capacity begins to drop as the cell-to-cell variation rises above about 15 mV in cycle 15. A more complete analysis is provided in [5].
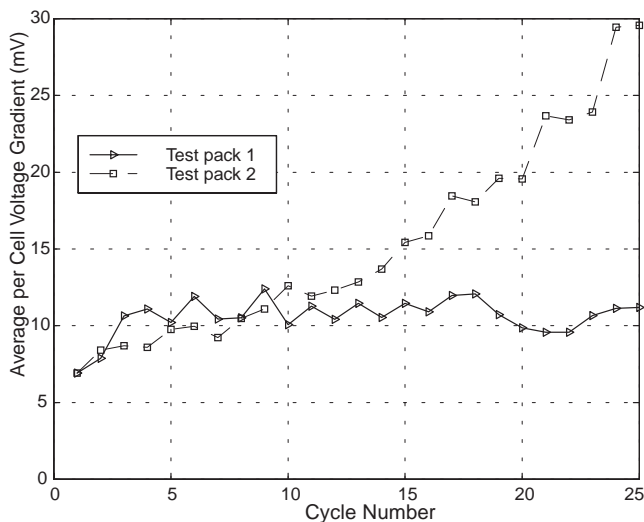

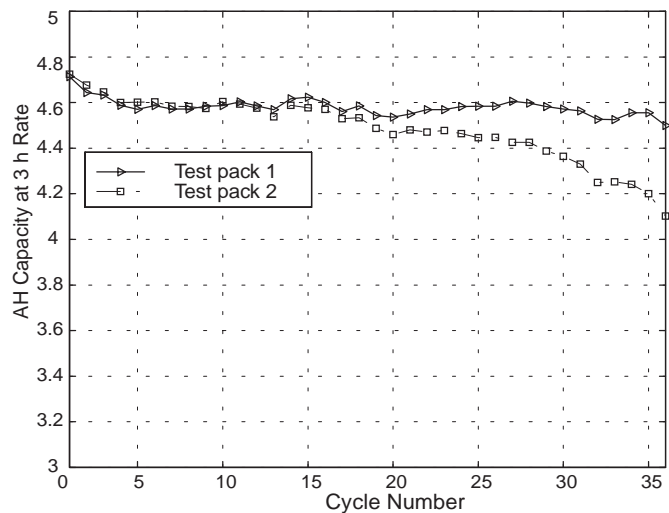Fig. 2. Cell voltage gradient for comparison test (from [5]).

Fig. 3. Cell capacity vs. cycle number for comparison test ([5]).

Based on the steady-state voltage behavior in Fig. 1 and the dynamic analysis in [5], we conclude that voltage matching is an effective way to match SOC for lead-acid batteries. This is true provided the currents are limited (the equalization current used in [5] is about 1% of the battery's nominal C rate).

The conclusion: To be useful, an equalization process should hold the cell-to-cell differences to about 10 mV or less. This is consistent with other results from the literature. In [8], for example, a large set of batteries is monitored cell-by-cell for condition management. The graphs in [8] show that good cells show balance to about 10 mV, while cells that deviate from this lose capacity and must be changed out.

Most practical rechargeable batteries have a monotonic relationship between voltage and SOC. The characteristic in Fig. 1 is useful because it is linear and unambiguous. In other cases, the result is more complicated. Lithium-ion cells, for example, show significant voltage change over the 0% to 100% SOC range. The relationship is monotonic but nonlinear. It would be expected that equalization would be beneficial for Li-ion strings. This has been confirmed in the literature [6,7]. Nickel chemistries show much flatter voltage-SOC profiles, and require very precise voltage matching to achieve good results.

III. WHAT ARE THE BENEFITS OF EQUALIZATION?

Modern rechargeable battery cells of all chemistries are specified by the manufacturer for hundreds or even thousands of cycles. Series strings of cells in general do not perform up to this level. The only difference between a single-cell and series-cell applications is management of individual cell voltages. This is the basis for many assertions in the literature that charge imbalance is the primary failure mechanism in batteries [1,2,8]. In principle, a perfect equalization process would ensure that a series string performs just like a single cell over time.

The need for equalization of VRLA batteries is clarified in other ways in [5]. For example in one test, several strings of 12 lead-acid batteries were cycled without equalization. The cells were rated for at least 400 cycles, but instead the strings provided only 25 to 30 cycles before reaching end of life. The charge profile did not provide the "overcharge" time (which largely involves equalization time) specified by the manufacturer.

The conventional equalization method is to provide a "forced overcharge" interval after the main charge sequence. The objective is to deliver full charge into the lowest cells. The process can be termed "passive equalization," since it relies on the properties of the battery cells to restore matching. Unfortunately, passive equalization works at the expense of gassing and dryout of the highest cells. In addition, it is a slow process. The forced overcharge equalization process is routinely used with lead-acid batteries.

When this process is used, 6 V or 12 V monoblocks become feasible. It is still true, however, that long-term monoblock failures usually involve a single cell that has weakened over time. For 48 V batteries, the results in [3] imply that intervals of several weeks will be required for equalization. Even if long intervals are available, the overcharge exposure can lead to thermal runaway. At higher voltage levels, results from [5] suggest that equalization time increases as the square of the number of cells.

A more effective equalization process is needed. Even for monoblock pairs at 24 V, an external active process to supplement passive equalization can accelerate matching and maintain cycle life. Figs. 4 – 7 (from [9]) compare passive and active equalization for a 72 V battery pack. Fig. 4 shows the voltages of the six 12 V monoblocks during charging. The passive equalization process is slow, and the three-day interval here shows no clear pattern. Active equalization, shown in Fig. 5, brings the voltages together rapidly. The operating results are emphasized in Figs. 6 and 7, which show the standard deviation of voltages among the six monoblocks in each string, corresponding to Figs. 4 and 5, respectively. Notice that passive equalization is really not reducing the voltage standard deviation, although perhaps it is starting to fall after about 60 h.
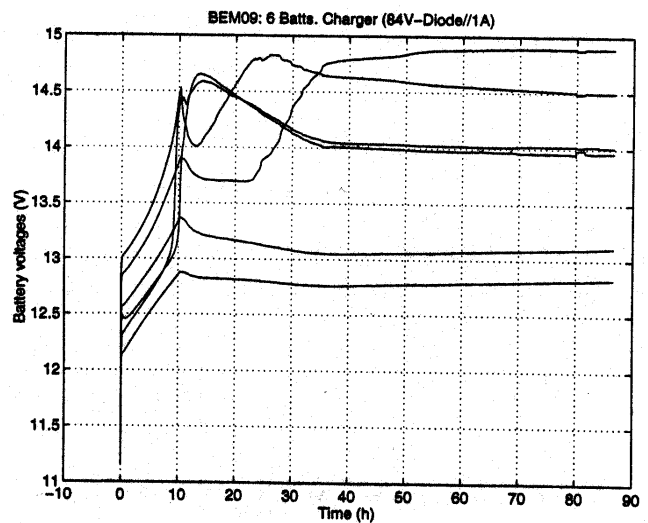

Fig. 4. 72 V battery string, charged under passive equalization (from [9]).
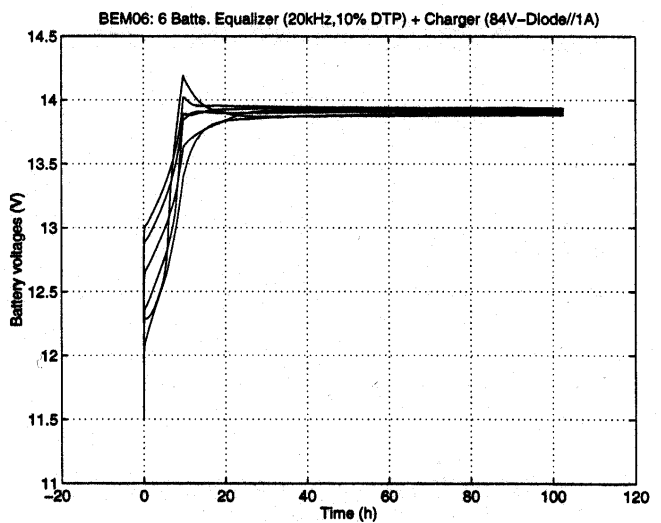

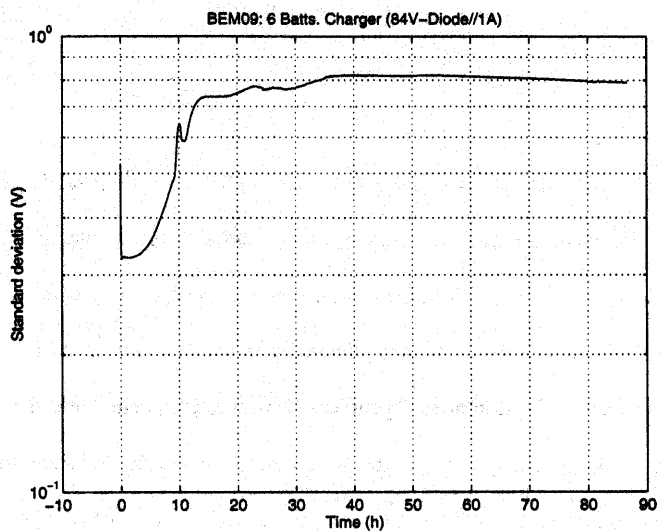Fig. 5. 72 V battery string, charged under active equalization (from [9]).

Fig. 6. Standard deviation of cell voltages, passive equalization (from [9])
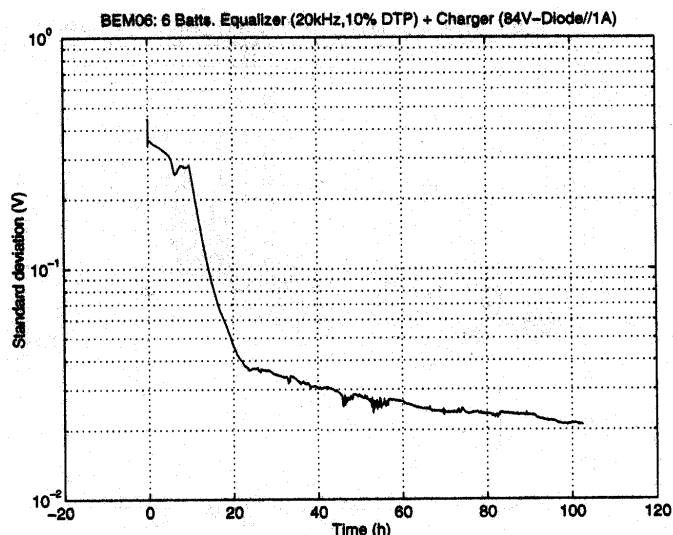
Fig. 7. Standard deviation of cell voltages, active equalization (from [9]).

The process presented in [9] has several key advantages over competing passive and active equalization technologies:

1. It is simple and direct, relying on a capacitor switching approach to equalization.

2. The voltage match is exact, regardless of errors or tolerances associated with real components.

3. The process consumes minimal energy, and can be used continuously throughout charge and discharge sequences.

4. The hardware is modular, and can be configured on a cell-by-cell or monoblock-by-monoblock basis. The technology lends itself very well to miniaturization.

5. The inherent cost is low because no high-tolerance components, controls, or specialty parts are needed.

6. Equalization proceeds independent of the charge process, so external current and voltage limits can be set and enforced without complications.

Assuming that equalization of voltage supports SOC matching, what can be gained? First, it would be expected that a series string of equalized cells would show life performance like that of an individual cell. This is potentially the most significant result – the 28-cycle performance of the unequalized charge test in [5] should extend right up to the manufacturer's rating of 400 cycles with proper charge limits. Second, failure modes associated with imbalance (repeated undercharge of weak cells, ultimately leading to failure) are avoided. Third, there is no need for forced overcharge as part of a cycle (given cell-by-cell equalization). This last is especially interesting, since it implies that perhaps the charge voltage limits can be decreased when active equalization is in place. Lower voltages make thermal runaway less likely, gas the cells less, and should avoid the stress on strong cells inherent in the passive equalization process.

Another important benefit is interchangeability. For example, many users recommend that series strings be built with tightly-matched cells. The basis for this is to start with as close a match as possible, perhaps allowing more cycles before cell imbalance becomes severe. With active

equalization, there is a process to drive the cells together, so tight initial matching is not needed. What if a failure does occur, perhaps because of a battery defect or other problem? Active equalization would support changeout of the defective battery or cell without introducing extra cell mismatch. The combination of long cycle life with the ability to change individual units rather than a whole string has potential for significant cost reduction.

In summary, effective equalization should

-- Extend cycle life of a series string up to that of an individual battery or cell.

-- Avoid failure modes based on cell imbalance.

-- Permit changeout of individual cells or monoblocks when a failure does occur.

-- Prevent weakening of string performance caused by individual undercharged cells.

All of these provide significant cost savings in battery installations. Longer-term, it should be possible to alter the charge process to take advantage of active equalization and further extend battery cycle life.

IV. WILL EQUALIZATION REALLY EXTEND BATTERY LIFE?

The above results suggest that cycle life can be extended at least up to the level promised by manufacturers for single cells or monoblocks. But can this be proven with real data? In fact, at least four published tests independently confirm the performance benefits of active equalization. Each is discussed individually here.

In [7], a distributed charging system was used. There were multiple chargers, and the effect is independent charging of small groups of cells. This is equivalent to an active equalization process on monoblocks. The chemistry was lithium-ion. Performance improvement was evident on the very next cycle after the distributed charging system was added: a 2% increase in total capacity was seen after just one cycle. Subsequent cycles showed additional improvement.

In [5], active equalizers were tested with conventional flooded lead-acid batteries. Active equalization maintained cell-to-cell matching of better than 10 mV throughout an intensive one-week accelerated test – even though a low float limit of 2.30 V/cell was used. For a second test pack, a higher voltage of 2.45 V/cell was used to drive a passive equalization process, but the cell deviation began to rise above 10 mV after only about six cycles. When water loss was measured over the test interval, the active equalization approach showed 40% less water loss than the passive method. The comparative water loss indicates cycle life extension on the order of 66%.

In [10], several different equalization methods were compared for effects on cycle life. Some of the methods actually degraded pack performance. A low-cost system built with the technology of [9] gave a 15% cycle life improvement – even though the design was probably undersized for the batteries being tested. A summary result from [10] is given in Fig. 8. The "Control C" curve represents a control battery pack that uses a manufacturer-recommended charge profile.

The "BMSC" curve is for the technology of [9], with exactly the same charge profile. (The profile target voltage was not reduced to take advantage of active equalization.)
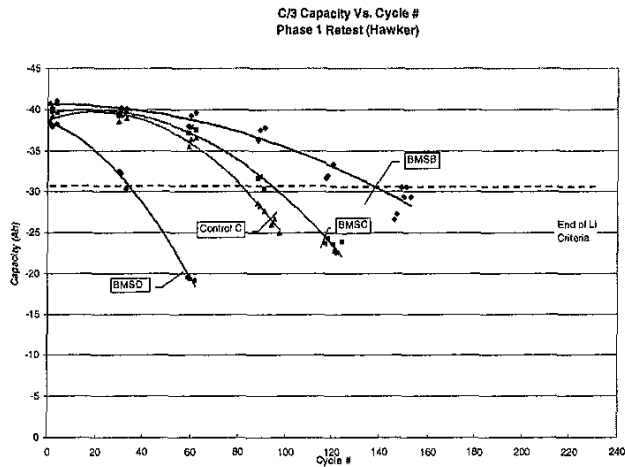

Fig. 8. Capacity vs. cycle for comparative equalizer test (from [10]).

In [11], cycle tests were performed on 48 V battery packs, with and without active equalizers. Fig. 9 (from [11]) shows the results – cycle life extension by about a factor of three. In this case, the active equalizers are sized appropriately, and can deliver sufficient charge to maintain cell balance. The technology used in [11] shares many performance characteristics of [9], although it requires precise control and is inherently more expensive. It is important to recognize that the result in Fig. 9 confirms that a series string should be able to reach cycle life levels similar to those of single monoblocks with an active equalization process in place. Pack 2, with active equalization, achieves at least 400 cycles – consistent with the manufacturer's rating for a single monoblock. Pack 1, which uses only a conventional charge cycle with passive equalization, reaches only about 140 cycles. The overall result is a tripling of cycle life for this 48 V pack.
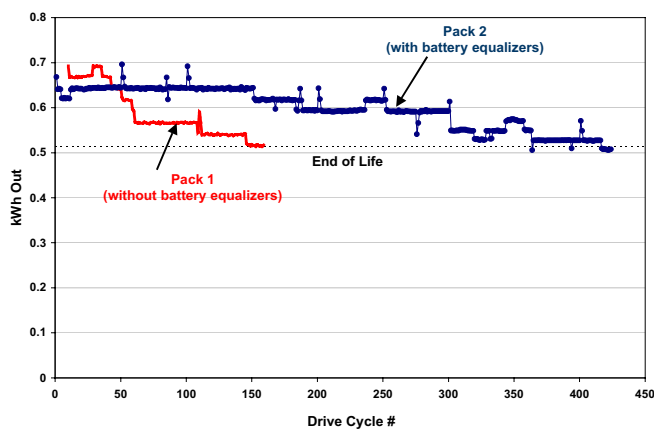

Fig. 9. Capacity vs. cycle, comparing passive and active equalization (from [11]).

Fig. 10 (from [12]), is a telling result. In this case, four different 24 V VRLA packs have been tested with two different charge profiles and various equalization strategies. Fig. 10a shows the capacity as it changes over repeated cycle tests, while Fig. 10b shows the voltage standard deviation as

the test proceeds. Battery pack 1 – the only one for which the standard deviation is held is about 10 mV – shows far better cycle life than the others. The figure confirms that performance degrades unless voltage imbalance is held to a low level, and provides a linkage between voltage-based equalization and cycle life performance. The results also confirm that voltage balance must be better than 10 mV/cell to provide benefits.
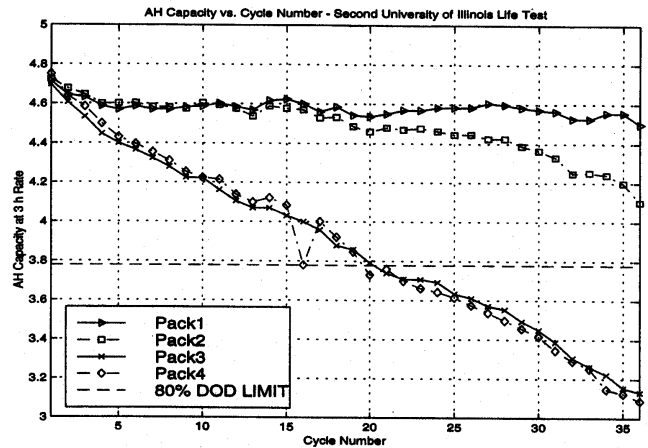
(a) Capacity vs. cycle number for four 24 V test packs
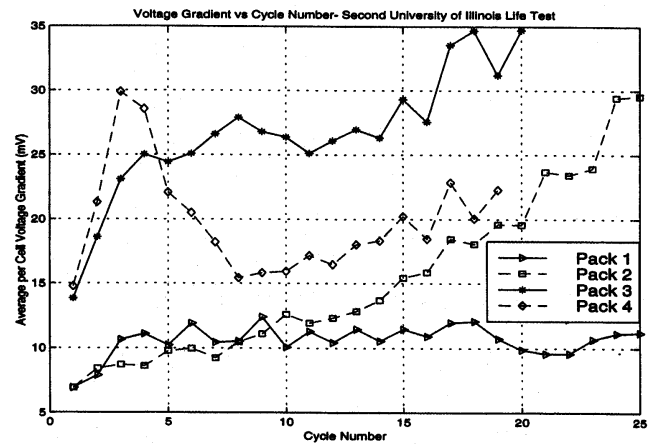
(b) Cell gradient (mV/cell) for four 24 V test packs

Fig. 10. Tests of four 24 V battery packs (from [12]).

Can active equalization technology provide precise enough balance to realize the benefits of equalization? Fig. 11 compares two packs, now being cycle-tested in the laboratory. The first uses passive equalization, while the second is supplemented with switched-capacitor active equalizers [13]. The standard deviation is only a few millivolts. This match has been maintained so far over several cycles, and results are building quickly. The technology of [9,13] matches voltages exactly. Provided sufficient charge exchange is supported, voltage differences well below 10 mV can be obtained.

In applications [14,15], the benefits of equalization have been immediately apparent. Overall pack performance improves noticeably as soon as equalizers are in place. In [15], a set of batteries revived from 0% SOC without developing any imbalance, thanks to equalization.
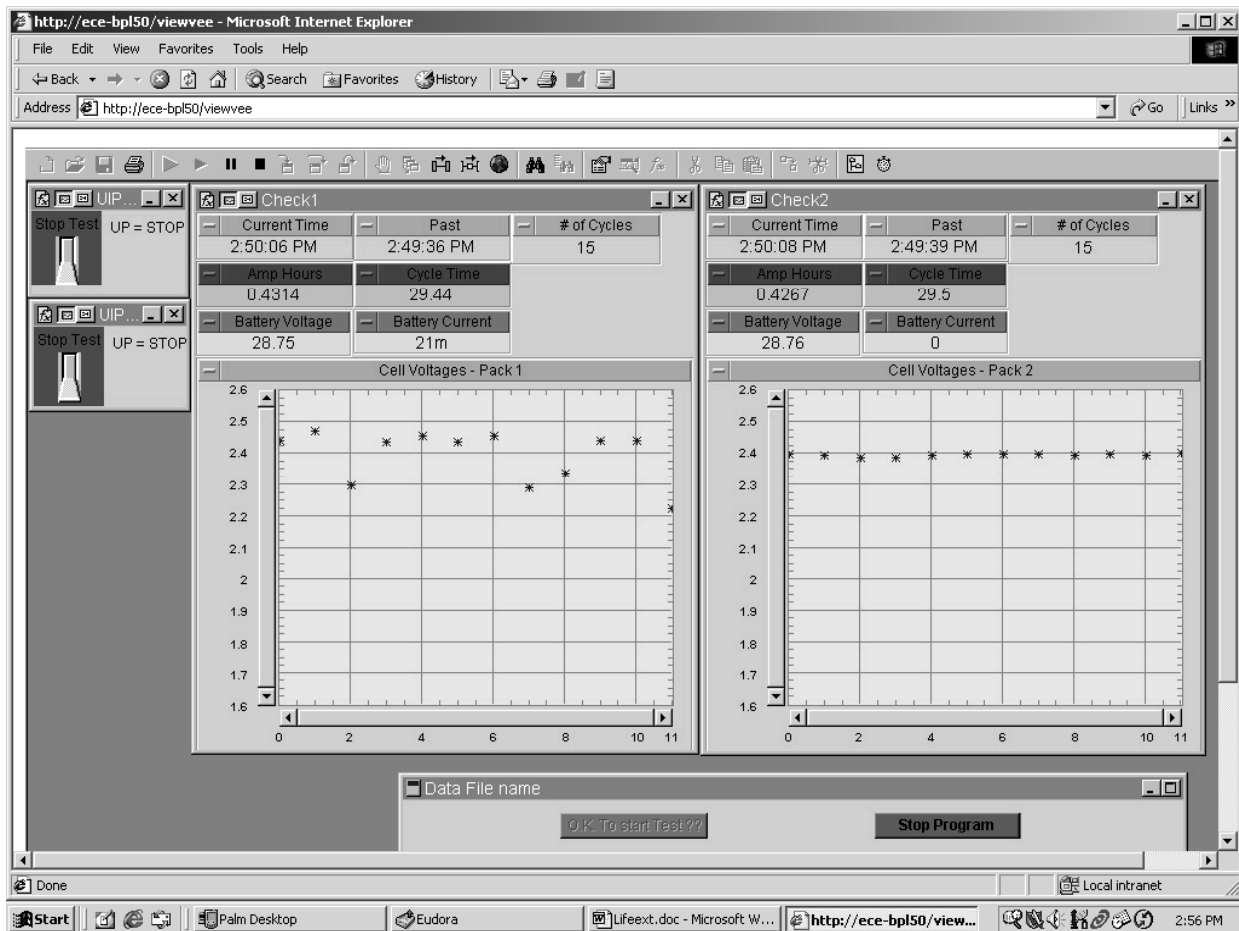
Fig. 11. Ongoing cycle test. Pack 1 uses passive equalization while Pack 2 uses active equalization.

V. CONTINUING RESULTS

At present, long-term cycle testing continues in our laboratory. Fig. 12 shows an example of voltages over several months of cycle testing. Fig. 12a are the cell voltages of the passively equalized pack and Fig 12b are the cell voltages for the actively equalized pack. Missing points reflect datalogging problems. In general, the cycles have been maintained without interruption for months. The gap at approximately 700 hr shows a change in charge-discharge sequence to match the recommendation of the manufacturer. In Fig. 13, a few cycles are shown in detail. The active equalization process, (Pack 2) shown in Fig 13b, brings voltages together quickly during the charge sequence and helps keep them close even during discharge. In Pack 2, one of the cells was weak from the beginning. While the equalizers have prevented it from getting worse, they do not provide a "repair" function, but the cell can be changed out without causing difficulty.

Fig. 14 shows an important summary result. Here, the cell voltage standard deviation is shown at the end of each charge process. The charge sequence recommended by the manufacturer (which begins at cycle 49) appears to be holding the voltage on the passive equalized pack reasonably well, although a slow increase appears to be underway. The

actively equalized pack, on the other hand, shows very tight voltage matching that is not degrading over time. Additional data will be available at the conference.

VI. SUMMARY

Effective use of series strings of battery cells requires cell-by-cell SOC matching to maintain performance. In general, SOC matching can be assured through precise voltage matching, although the matching must be excellent (10 mV in the case of lead-acid cells) for success. Conventional passive equalization works for short series strings (six cells, and perhaps up to twelve), but puts stress on strong cells and loses effectiveness rapidly as the series string becomes longer. If equalization can be assured, it provides substantial benefits such as longer cycle life, fewer failure modes, and simpler maintenance. These translate into major cost savings for large-scale rechargeable battery applications. The technology of [9, 13] provides perfect voltage matching without any sensing or control, and is the lowest-cost active equalization method known. All results to date indicate that it can successfully deliver on the promises of performance improvements under equalization.
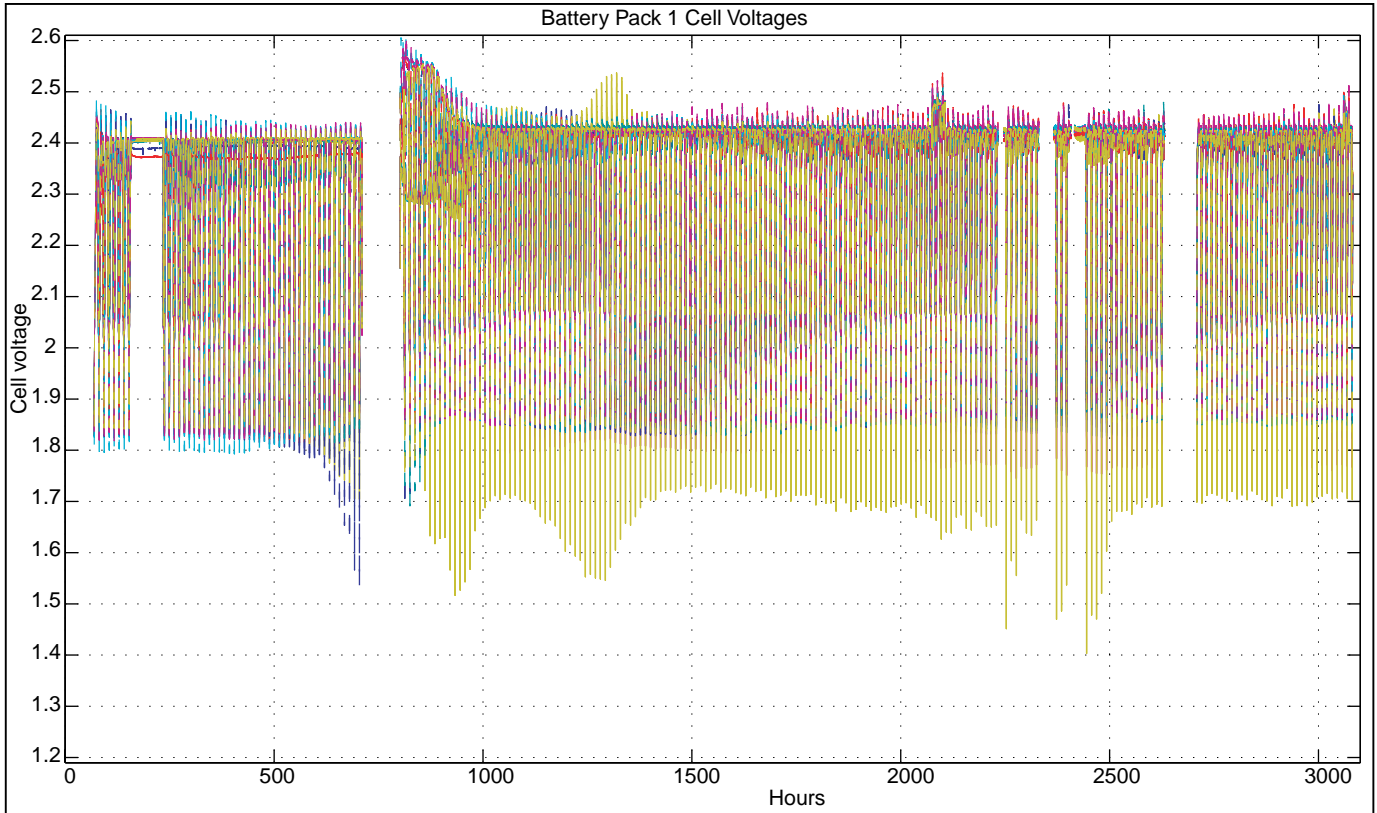
Battery Pack 1 Cell Voltages

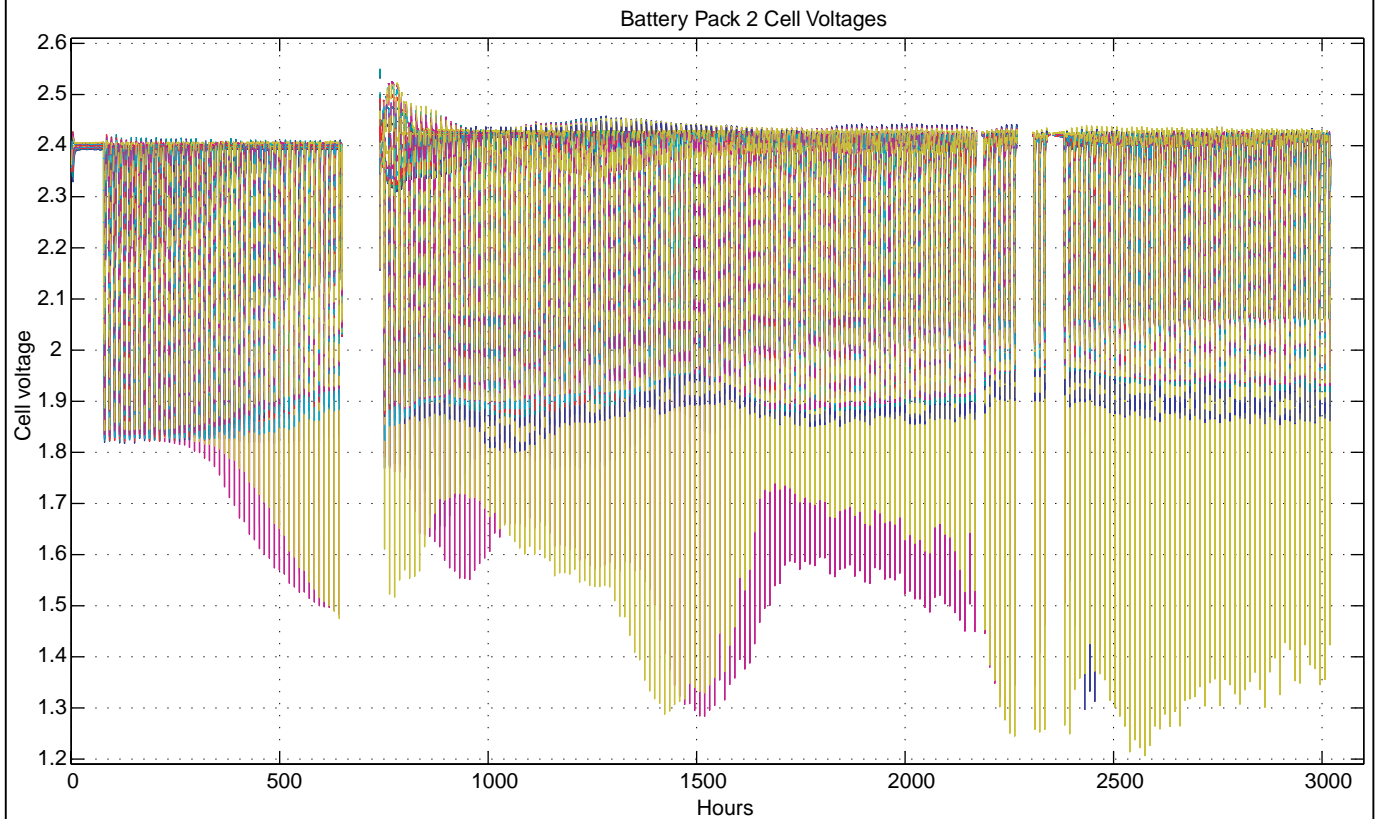Fig. 12a: Passive equalization

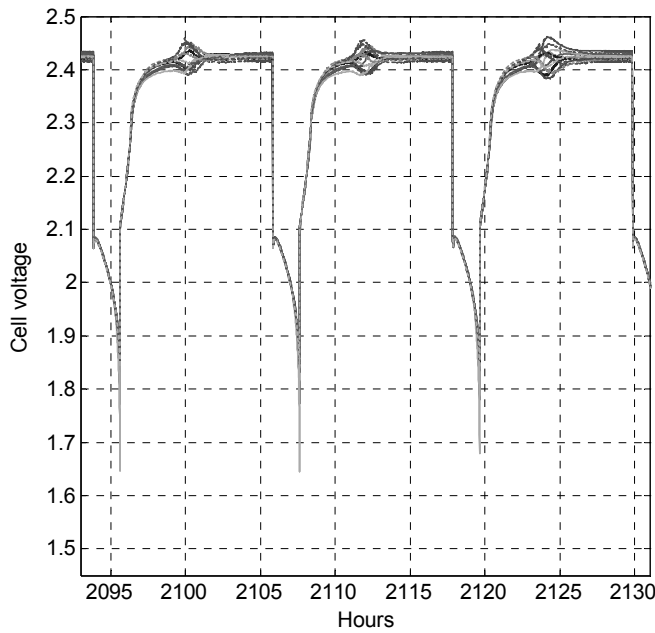Battery Pack 2 Cell Voltages

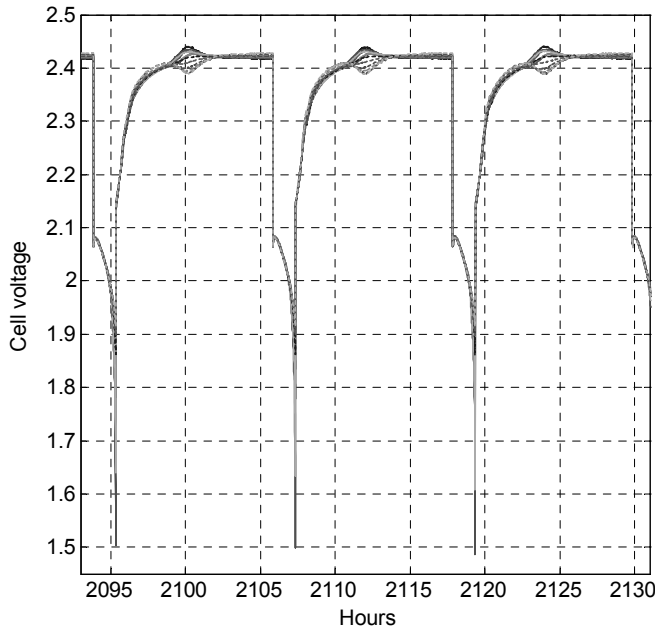Fig. 12b: Active equalization

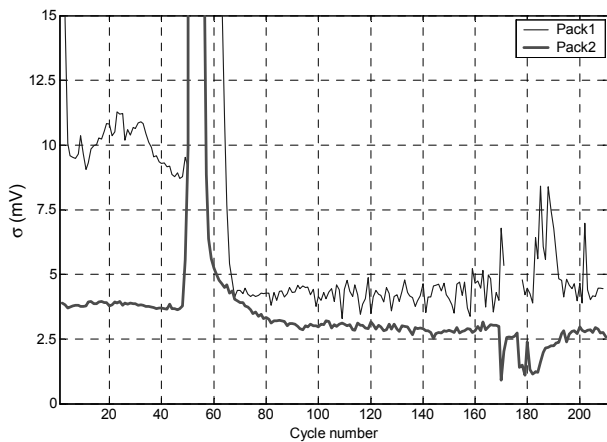Fig 13a: Passive equalization

Fig 13b: Active equalization

Fig 14: Standard deviation of cell voltages at end of charge

REFERENCES

[1] Ron D. Brost, "Performance of valve-regulated lead acid batteries in EV1 extended strings," in *Proc. IEEE Ann. Battery Conf. Appl. Advances*, 1998, pp. 25-29.

[2] J. B. Olson, E. D. Sexton, "Operation of lead-acid batteries for HEV applications," in *Proc. IEEE Ann. Battery Conf. Appl. Advances*, 2000, pp. 205-210.

[3] A. Lohner, E. Karden, R. W. DeDoncker, "Charge equalizing and lifetime increasing with a new charging method for VRLA batteries," in *Proc. IEEE Int'l. Telecommunications Energy Conf.*, 1997, pp. 407-411.

[4] R. O. Hammel, A. J. Salkind, D. Linden, "Sealed lead-acid batteries," in D. Linden, ed., *Handbook of Batteries, 2nd e*d. New York: McGraw-Hill, 1995, p. 25.10.

[5] S. West, P. T. Krein, "Equalization of valve-regulated lead-acid batteries: issues and life tests," in *Proc. IEEE Int'l. Tele-communications Energy Conf.*, 2000, pp. 439-446.

[6] M. J. Isaacson, R. P. Hollandsworth, P. J. Giampaoli, F. A. Linkowsky, A. Salim, V. L. Teofilo, "Advanced lithium ion battery charger," in *Proc. IEEE Ann. Batt Conf. Appl. Advances*, 2000, pp. 193-198.

[7] T. T. Sack, J. C. Tice, R. Reynolds, "Segmented battery charger for high energy 28 V lithium ion battery" in *Proc. IEEE Ann. Batt Conf. Appl. Advances*, 2001, pp. 157-159.

[8] T. L. Churchill, "Battery condition management: an important way to protect a critical asset," in *Proc. IEEE Ann. Batt Conf. Appl. Advances*, 2000, pp. 71-76.

[9] C. Pascual, P. T. Krein, "Switched capacitor system for automatic series battery equalization," in *Proc. IEEE Applied Power Electronics Conf.*, 1997, pp. 848-854.

[10] R. E. MacDougall, J. D. Bertolino, K. L. Rodden, E. T. Alger, "Lab testing of battery charge management systems for electric and hybrid vehicle battery packs to evaluate cycle life improvement," in Proc. IEEE Ann. Batt Conf. Appl. Advances, 2000, pp. 237-242.

[11] N. H. Kutkut, "Life cycle testing of series battery strings with individual battery equalizers," white paper, Power Designers, Inc., Madison, WI, 2000. Available: http://www.powerdesigners.com/products /PowerCheq/HEV_Paper.pdf.

[12] S. West, "Performance evaluation of switched capacitor battery equalizer," M.S. Thesis, University of Illinois, May 2000, p. 84.

[13] C. Pascual, P. T. Krein, "Switched capacitor systems for automatic series battery equalization,"
U. S. Patent 5,710,504, January 1998.

[14] J. A. Cellarius, S. P. West, P. T. Krein, R. A. White, "Design and development of a power tracking series-type hybrid vehicle," in 1999 FutureCar Challenge (Warrendale, PA: Society of Automotive Engineers, 2000).

[15] J. A. Locker, private communication with respect to operating results of Sunrayce '97, June 1997.