Distributed Battery Monitoring Sensors
Effects and Suggested Solutions

Nigel Scott
Director
Custom & Contract Power Solutions Ltd
Scotland

Note: The terms 'cell' and the new designation 'unit' are interchangeable for the purpose of this paper.

Distributed Battery Monitoring Systems (BMS)

The advent of widespread computer technology in the 1970s brought with it the need for uninterruptible power supplies (UPS) and these power systems in turn relied on lead-acid batteries for their continuous power support. Within a short time several US companies, saw a commercial opportunity, and individual cell continuous monitoring systems for lead-acid standby batteries have been marketed since the 1980s.

With two notable exceptions, the first systems only monitored cell voltage and ambient temperature, and perhaps current, and had a single monitor or grouping system to which all the cells were connected directly, via long wiring harnesses.

In the in the mid 1990s a British BMS company introduced the idea of multi-frequency impedance and a distributed sensor system, comprised of one sensor integrated with each cell, and communicating via a serial link with a central monitor, and this has become the prevalent architecture.

Today some BMS companies prefer their original central monitor systems and some a distributed system; therefore since the late 1990s there have been two types of system in the standby Lead-Acid battery monitoring industry, they are:

1. A distributed architecture (Figure 1a) in which individual sensor modules monitor one or more cells each, and where the sensors are located on or adjacent to the cell being monitored. This type of system is now in the majority.
2. A traditional centralised system (figure 1b) where long wires are taken in a harness from each cell, taken directly back to a central monitor or grouping system.

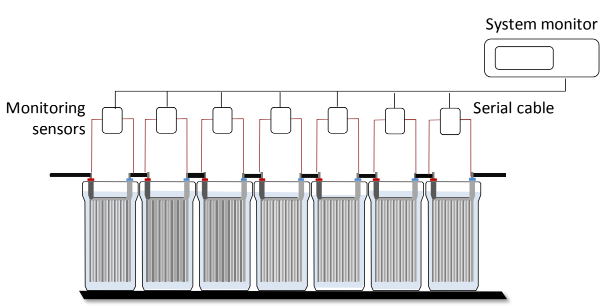


Figure 1a: Distributed BM sensors

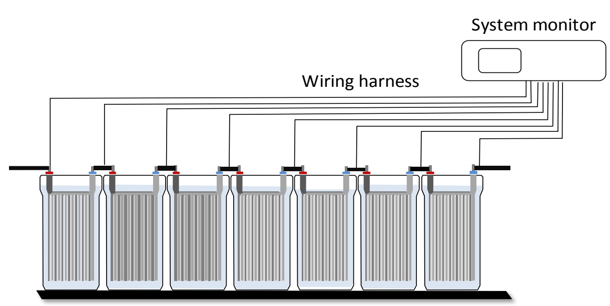


Figure 1b: Central monitor, wiring harness

Both types can be said to have arguments for and against. In distributed systems the main argument against is that the current to power the sensors is taken from the cells that the sensors are integrated with.

If this is the case there is a risk of some cells having a portion of their float current diverted to the attached sensor and thus undercharged (this is also true for two and four-cell sensors), and vice-versa, some cells may be overcharged where the sensor draws less current than others.

Proponents of distributed systems assert that, since the sensor modules are in series with each other and connected to the charger at both ends, the supply current comes directly from the charger and not from the battery cells.

The pertinent factor in the supply of current to both the cells and the sensors is that in standby batteries once the charger voltage is set at commissioning, there is no current control and other than temperature correction or opportunity charging, this voltage never varies.

In fact, both camps are partially right and both are partially wrong.

Voltage and current in electrical circuits

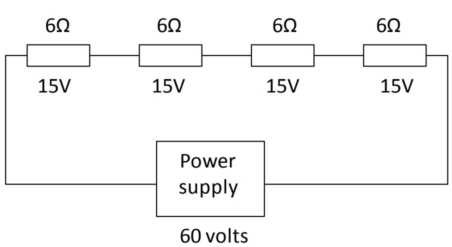


Figure 2a: Identical series resistances

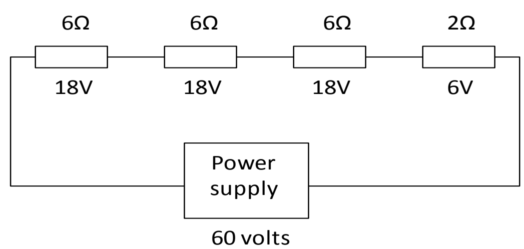


Figure 2b: Dissimilar series resistances

In an electrical circuit where all components are in series, the current is always the same at any point in the circuit. Thus if four identical resistors are connected across a power supply (figure 2a), all the resistors will have the same current flowing through them, and because the potential difference (voltage) across a resistor is the current multiplied by the resistance, the voltage will be the same across each resistor.

Now if one of the four resistors is changed for one of a lower value (figure 2b), the same current flowing through all resistors means that the voltage across the lower resistance will be less than the resistors with the higher values (voltage equals current times resistance). Because the power supply voltage is fixed, as in the previous example, the other resistors will develop a higher potential difference to compensate for the lower voltage across the 2 Ohm resistor.

Standby Batteries

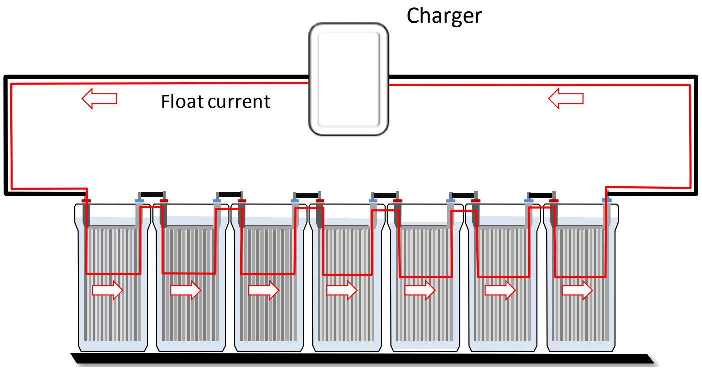


Figure 3: Battery cells in series with the charger

In standby batteries, a single series circuit is called a string, and the electrical law for the resistance circuits in 1a and 1b is also true of charging circuits for battery cells in series, in that the same current will flow through all the cells in the circuit (Figure 3). Providing all the cells in the circuit are identical, all will develop the same potential difference across their terminals.

All lead-acid standby (stationary) batteries, whilst in service, are subject to a low maintenance 'float' charge of a few tens or hundreds of milliamps continuously, to maintain their readiness to supply energy 'instantaneously' when required. The float voltage for the battery as a whole is fixed by the charger/rectifier at, for example, 2.25 or 2.26 Volts per Cell (VpC) multiplied by the number of cells in the string;

Variance in cell terminal voltage of the magnitude of figure 5 is an undesirable situation, as some cells will be undercharged and some overcharged. If the difference is significant and the situation persists for some time, the lower voltage cells will be subject to premature sulphation, and the higher voltage cells to corrosion of the positive plate electrode.

The mismatching of series lead-acid cells in standby applications is caused by the difference between the cells' fully charged open circuit voltage and the float charge voltage imposed by the charger. The charge acceptance of the positive and negative plates when the cell is charged will dictate the plate polarisation and thus the open circuit voltage of the fully charged cell. The difference between this and the amount of float charge overvoltage (figure 4) in turn determines the float current for that cell.

A combination of all the O/C (polarisation) and overvoltage differences in the string are what determines the amount of float current through the battery as a whole.

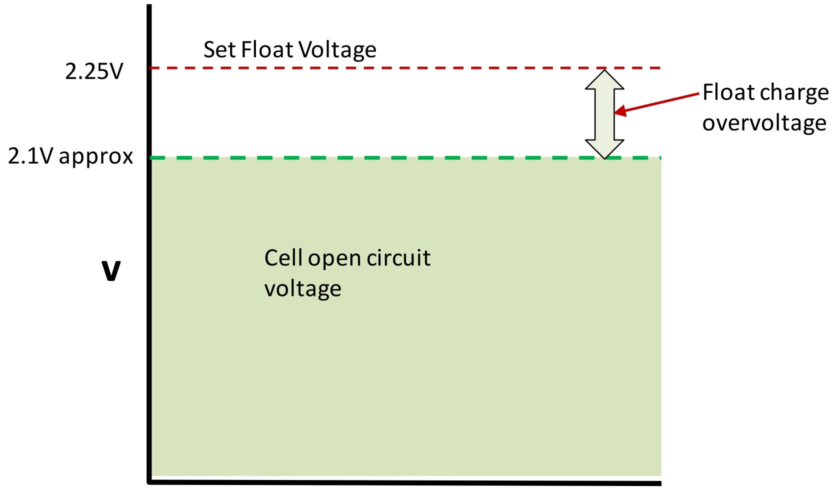


Figure 4: The float charge overvoltage of a cell

In fact no two electrochemical cells are identical, and when installed the differences can mean different, mostly minor, float voltages for each cell. Figure 5 is a graph of a six year old battery in a large data center; the unit terminal voltage differences can be clearly seen.

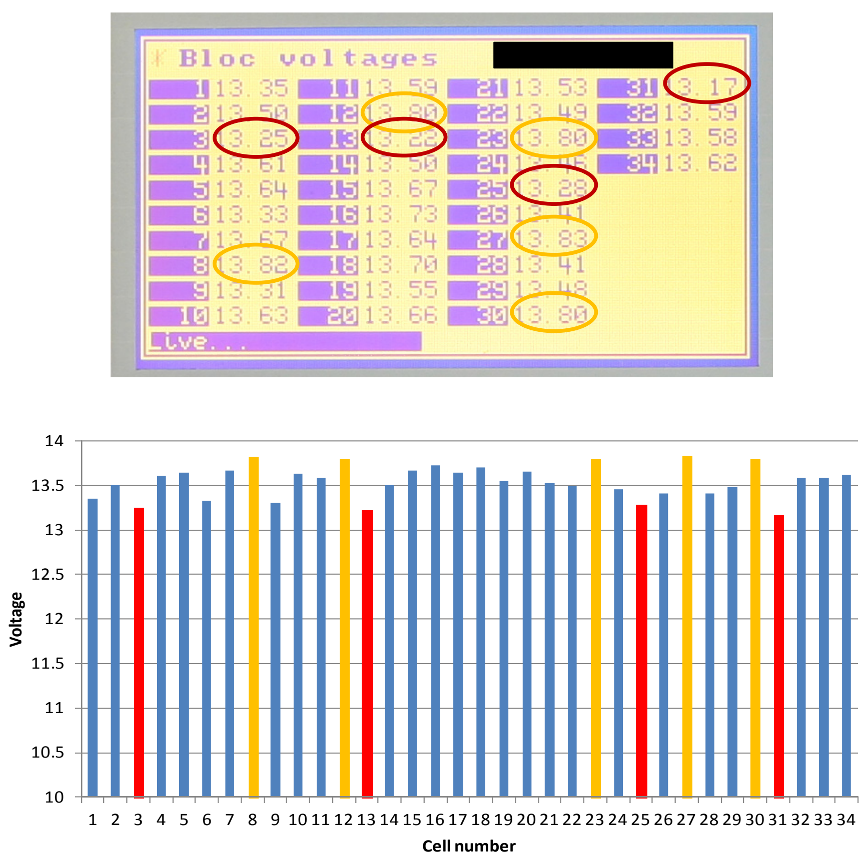


Figure 5: An actual measurement of a section of an in-service data center battery

In lead-acid batteries, whether Valve Regulated Lead Acid (VRLA) or flooded, differences remain while the cell is in service. In the majority of battery systems the differences are minimal; significantly abnormal cells are only present in a minority of batteries and differences may not be apparent in the early part of the battery's service life, however it is more common than is generally realised.

Continuous Battery Monitoring

When battery monitoring sensors are attached to the individual cells as shown in figure 6, they are effectively in series with the battery charger and, in a simple series circuit without the battery attached this would be fine, however once the sensors are attached to the cells each sensor is also in parallel with each cell, or cells, and this is where the complications come in.

In an ideal situation each sensor would each draw exactly the same amount of supply current as its neighbours and, if this were the case, given that the cells were also of identical voltage, then either the sensor current will come directly from the charger or, if the sensors drew their current from the cells, all the cell voltages would depress together and the charger current would increase to compensate.

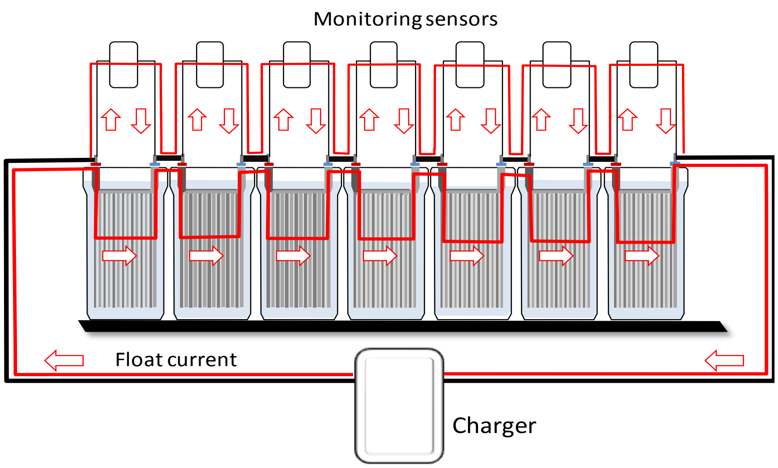


Figure 6: Individual cell monitoring sensors; current diagram

Therefore in this situation the cells are only the means of setting the voltage across each sensor, and are either not supplying any of the current required for the sensors, or the sensor current is coming from the cells, but is being replaced by the charger current. Both situations result in a current balance for the all the cells, which are maintained at the correct terminal voltage.

Of course not every situation could be called ideal.

Sensor architecture: All distributed battery monitoring sensors are internally powered, either by a circuit called a switched mode DC/DC converter or a linear regulator, or by a mix of the two. A DC/DC converter boosts cell voltage up to the sensor operating voltage, i.e. 2 or 4 volts up to 5 volts, and a linear regulator brings 6 or 12 volts down to 5 volts. Some circuit designs can perform both functions.

DC/DC converter and regulators, like all other electronics, work to tolerances. A cheap DC/DC converter or regulator might be accurate to +/- 10%, an expensive one +/-3-5% and a very expensive one +/-1% or less. The latter is likely to exceed the manufacturing cost of a complete battery monitoring sensor.

Taking a reasonably expensive unit as an example; +/-5% means that there can be a difference in the current draw between any two sensors in a string of up to 10%. If cheaper ICs or less accurate components are used the difference can be up to 20% between sensors.

Worse, a characteristic of a switching converter is that if its supply voltage (the cell) goes down, the DC/DC converter will increase its current draw to supply power for its own requirements. Needless to say, this can only make matters worse for the voltage at the cell terminals.

When this situation occurs in a battery installation, the higher current drawing sensors will depress the terminal voltage of the cell they are connected to, and the sensors with lower current requirements will allow their cells to float up.

Neither situation is desirable and over time, if significant, can result in premature sulphation, positive grid corrosion and/or thermal runaway.

Battery cell + sensor voltages: Some of the cell terminal voltages in a string may be less or more than their neighbours; if this is combined with a current draw imbalance in the sensors, the differences can become more severe.

Case study

Below is an actual example of a BMS where the modules are monitoring two single cells each. The battery is a 60 cell flooded type and had not been installed for any great length of time.

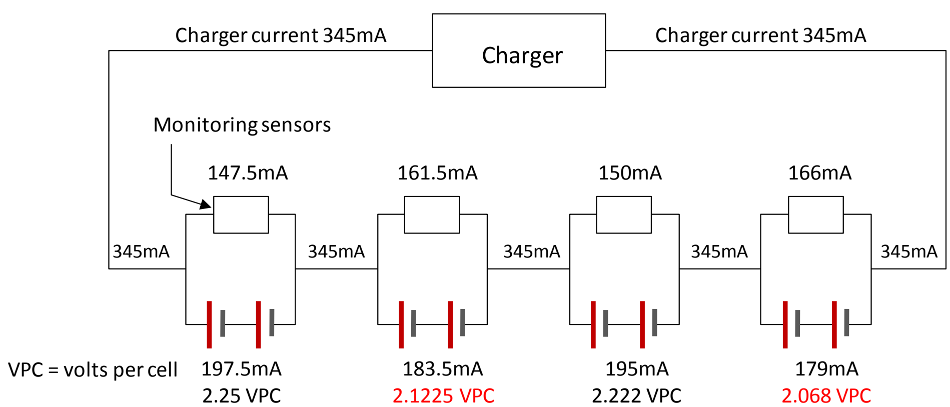


Figure 7: Extract from an actual in-service battery of 60 cells, 400 Ampere-hours, monitored by dual cell sensor modules

It can be seen from the in-service example in figure 7 that at least four cells out of the 60 cell battery are being charged at a float voltage too low to charge fully or prevent sulphation. Although in figure 7 the charger is supplying the majority of current to the monitoring sensors, the imbalance in the current draw of the sensors causes the small amount of extra current required by sensors which have a higher current requirement to be drawn from the cells they are monitoring. This reduces the amount of float charge the cells are receiving and causes the voltage across the pair of affected cells to reduce.

Can these imbalances be corrected?

There are one or two methods of combating the problem of differing cell voltages:

1. Have the sensors enter a sleep mode between measurement scans (this assumes the scans have a period of some minutes between them). This may not be totally effective, but better than no action.
2. Match the sensors for current draw before they leave the factory, a better option, especially when combined with (1)
3. Employ a method of cell terminal voltage optimisation

Looking more closely at the last method (3):

Active and passive cell terminal voltage optimisation

Individual cell balancing has been around for a long time; Lithium cells could not operate without it. In general it works well, and with Lithium close control of the cell voltages is mandatory.

In stationary lead-acid batteries, past experiments commercially with balancing cell voltages individually, admittedly without close control, have resulted in one or two significant failures, and the standby industry is now to some extent resistant to the idea of individual cell optimisation.

However technology and understanding of the life processes of these batteries has moved on in the last decade or so and, using an intelligent optimisation system, the terminal voltage of the individual cells can now be controlled in such a way as to ensure that the cell is not over or under charged. At least one (European) company has installed many tens of thousands of sensors employing passive terminal voltage optimisation in both Europe and the US without any reported faults.

There are two ways that this individual cell control can be achieved, passive and active cell voltage optimisation.

1. Passive cell optimisation

This is a simple but limited system which takes advantage of the fact that the whole battery terminal voltage is fixed by the charger/rectifier. Any cell terminal voltage optimisation requires a module per cell, or at least individual cell control; however any monitoring system which has one module per cell and can test for resistance or impedance can passively balance the cells.

Essentially, passive balancing is effected by connecting a resistance across the terminals of each cell which has a higher than desirable terminal voltage (figure 9). This will have the effect of diverting some of the float current through the resistance and away from the cell itself. Because there is a reduction in float current passing through the affected cell, the cell terminal voltage itself will go down.

At least one battery monitoring manufacturer achieves this diversion of float current by putting most of the sensors in sleep mode and leaving the sensors which require the terminal voltage to be powered on permanently.

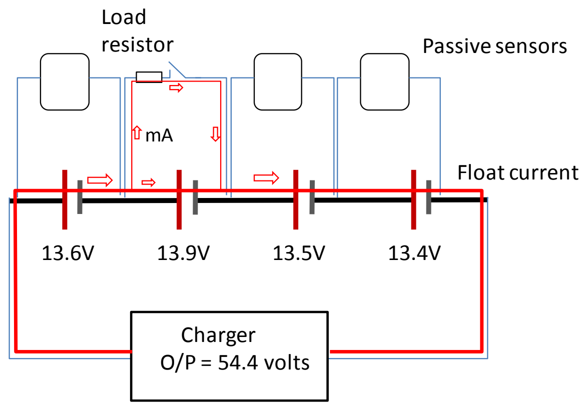


Figure 9: Passive cell terminal voltage balancing

Needless to say, a sensor which monitors more than one cell cannot adjust the cell voltage, since all the cells it is monitoring/controlling may not have the same requirement, but would receive the same current diversion. An alternative available to distributed systems which monitor only one cell per sensor is to operate the sensor continuously. This will have the desired effect of diverting some float current from the cell, as if a resistor had been connected across it.

Since the voltage at the main battery terminals is fixed by the charger, reducing the terminal voltages of the higher cells has the effect of forcing the lower voltage cells to rise a millivolt or two each, until equilibrium is reached.

The limitation in passive balancing however is that only higher voltages can be addressed; cells with lower than optimum terminal voltages cannot be optimised by the passive system and this can be a problem which leads to other problems. Also, diverting a few milliamps from a low ampere-hour cell is possible, but the problem becomes more difficult on larger cells of several hundred ampere-hours.

For example, if two cells in a string of 24 are too low, the other 22 must be a little high, but not necessarily by enough to trigger a float current bypass.

1. Active cell optimisation

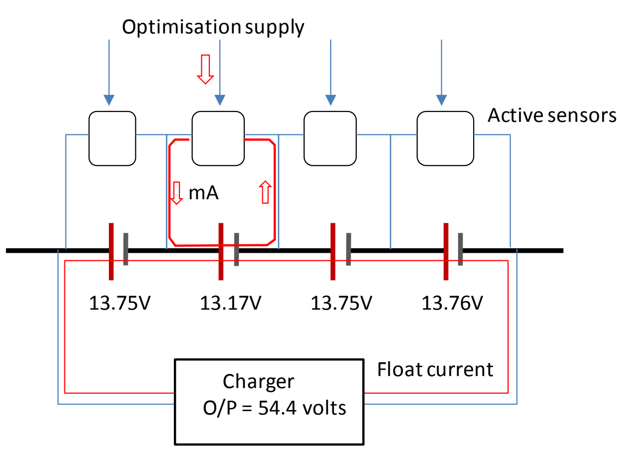
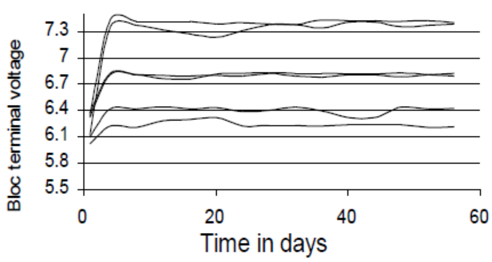


Figure 10: An active cell terminal voltage system, with a supply independent of the battery

In this system (figure 10), an active bi-directional energy transfer device is included in every sensor and coupled to all the cells in the string or strings. The sensor module is then supplied with current from a source external to the battery; thus an active system can both inject and remove a small amount of energy into the cell dynamically.

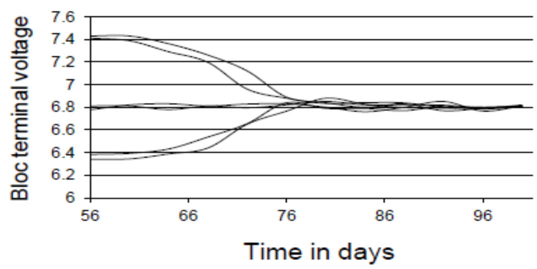
Active systems are to be preferred for several reasons, for example, if one or two low float voltage cells in perhaps 24 cells can receive a small amount of current to bring them back into the manufacturers recommended float band, without any disturbance to the other cells; this is not possible with passive systems.

The graphs in figure 11a & b are actual voltage readings from 6 x 5-year old Yuasa units tested in the laboratory, charged with a fixed voltage of 41 volts. The unit resistances were within a few percent of each other; when fully charged and discharge tested all were within 5% of specification.



6 x Yuasa 5-year old 100-6 blocs on float charge in excess of 55 days; charger voltage fixed at 41 volts

Figure 11a



Cell balancing activated after 60 days, terminal voltages merge after 17 days operation

Figure 11b

Active versus passive optimisation, example

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

Figure 12: VRLA Plant-years expected for passive and active terminal voltage optimisation to within .015VPC of optimum. Sample: 2538 batteries in 846 strings. (expected average life = plant-years divided by number of units) [Lifetime effects of voltage and voltage imbalance on VRLA batteries in cable TV network power; Brian Kuhn, René Spée, Philip T Krein, Proc IEEE INTELEC 2005]

The authors of the paper in figure 12 perceived advantages for active optimisation over passive, and passive over no optimisation. Figure 12 shows the lifetime test results on 2538 batteries in a TV cable network company in the US; the authors state convincingly that an active equalization system is required in their battery plant for optimum life expectancy.

Summary

Cell optimisation, for or against?

For BMS sensors: When a distributed battery monitoring system with one or more cells per sensor is installed on a standby battery, unless the sensor's internal power supply is of the highest order, i.e. less than 1% accuracy, it makes a great deal of sense to have the ability to actively optimise the input of the sensor, so that it is not an additional load on the cell.

Any differences may not make themselves obvious for some time, therefore it shouldn't be assumed that if it all looks good on installation that is the way it will stay.

When the cells themselves are at variance: This is a more contentious issue; proponents of cell terminal voltage optimisation make large claims that the optimising the individual cells to the manufacturers recommended float voltage can:

1. Prevent early sulphation (undercharging)
2. Prevent early positive plate corrosion (overcharging)
3. Prevent loss of electrolyte/dryout (overcharging)
4. Prevent thermal runaway (raised float voltage & current)
5. Guarantee full charging of every cell
6. Give a strong case to a manufacturer for guarantee replacement of failing cells
7. Extend service life by up to 30% (to the maximum design life)

It is difficult to argue for or against these points without a great deal of lifetime evidence, although the premise is seductive. However if, after extended development & testing, a manufacturer states that the optimum float voltage for his product is a certain voltage then, all other things being equal, it is reasonable to expect that the best performance and longest service life can be expected from a cell maintained at that voltage. Certainly it has been suggested that a cell that has a terminal voltage that is much at variance with the manufacturer's recommendation (+/- 0.015V [ii]) could not be relied on to perform perfectly.

The user must make up their own mind about the usefulness of cell optimisation generally; however it certainly can be argued that optimising the *sensor* voltages to cancel the effects of unbalanced voltage has a place when distributed BMS sensors are employed.

References

I. J. W. Kimball et al., "Increased Performance of Battery Packs by Active Equalization," *Proceedings of the IEEE Vehicle Power and Propulsion Conference, 2007. VPPC 2007*, Institute of Electrical and Electronics Engineers (IEEE), Sep 2007.

II. Life Extension Through Charge Equalization of Lead-Acid Batteries Philip T. Krein, *Fellow, IEEE*, Robert Balog, *Student Member, IEEE* INTELEC 2002 Paper 32.1

III. Lifetime Effects of Voltage and Voltage Imbalance on VRLA Batteries in Cable TV Network Power, Brian Kuhn, René Spée, Philip T. Krein 10.1109/INTLEC.2005.335098 18-22 Sept. 2005

IV. Life Cycle Testing of Series Battery Strings with Individual Battery Equalizers, Nasser H. Kutkut, PowerDesigners, LLC

V. S. Bergvik, Prolonged Useful Life and Reduced Maintenance of Lead-Acid Batteries by Means of Individual Cell Voltage Regulation, î INTELEC Conf. Proceedings, pp. 63-66, 1984.

VI. Lifetime effects of voltage and voltage imbalance on VRLA batteries in cable TV network power; Brian Kuhn, René Spée, Philip T Krein, Proc IEEE INTELEC 2005]

VII. Charge Equalization Systems for Serial Valve Regulated Lead-Acid (VRLA) Connected Batteries in Hybrid Power Systems Applications K. Belmokhtara *, H. Ibrahima,b*, Z. Fégera , M. Ghandourc, 10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, Düsseldorf, Germany