IMPROVING THE PERFORMANCE OF STATIONARY BATTERY STRINGS VIA INDIVIDUAL BATTERY EQUALIZATION

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ABSTRACT

This paper verifies the performance improvements of stationary battery strings via individual battery equalization. A study of two battery strings with each consisting of two old batteries and a new one was conducted. One of the strings was equipped with PowerCheq equalizers, a new battery equalization device. Both strings were cycled through a regime of shallow discharge cycles simulating a stationary battery system. The data clearly shows that the string equipped with the individual battery equalizers outperformed the other string. The individual battery equalizers allowed the new battery to operate well with the old batteries and limited the degradation in battery string's performance due to the mismatch in battery capacities. The use of modular, real-time individual battery equalizers allows batteries to stay equalized during charge as well as discharge cycles thus improving battery life and longevity.

I. Introduction

Series battery strings are used as the main power source in many cyclic and stationary applications. In almost all applications, the battery string is treated as a single unit and all batteries within the string are assumed to be exactly the same. This is far from reality. Differences in cell chemistry and normal differences during repeated cycles of cell charge and discharge lead to large non-uniformities in cell charge levels and correspondingly dissimilarities between individual cells. In fact, dissimilarities between individual cells/modules can be attributed to many factors including:

- Normal (chemical) differences between battery cells/modules
- Differences in charge acceptance rates
- Differences in discharge capacities
- Differences in grid deterioration rates

These differences give rise to cell imbalances, which lead to reduced string capacity and reduced life. As a result, efforts to reduce cell imbalances will positively impact battery life and performance.

Almost all series battery strings are charged serially using a single charger. This often leads to improper charging of some cells within the string, namely undercharging and/or overcharging.

Undercharging of batteries leads to reduced cell capacities and potential sulfation, which is the formation of large crystals of lead sulfate. Overcharging, on the other hand, leads to the loss of lead (loss of life), the loss of electrolyte, and a potential thermal runaway. Figure 1 shows an example of a four battery string being charged by a single charger and the potential for having both undercharged and overcharged cells. Achieving proper charging on a per cell/module level for series strings is quite challenging.

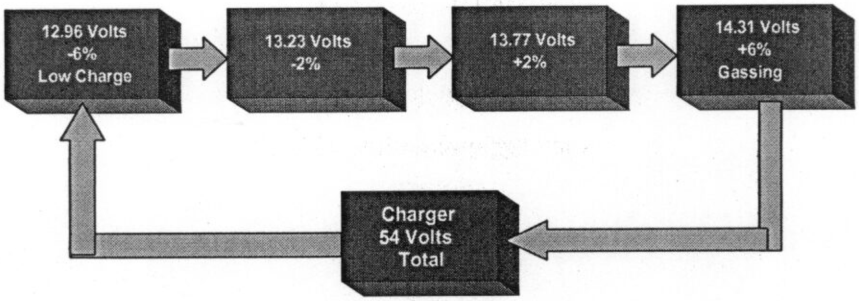

Figure 1: Serial charging of a 4-battery string

II. String Equalization

One technique that has been widely used to overcome improper charging in series battery strings is string equalization. As series string chargers are unable to distinguish or address dissimilarities between individual cells, string equalization attempts to solve part of the problem through charging up undercharged cells.

String equalization is normally achieved by applying an extended period of "float charge". The main goal is to allow undercharged cells to develop full state of charge through the extended overcharge period. Although this technique addresses the issue of undercharged cells within a string, it often causes overcharging of good cells while masking high resistance cells. A false sense of security is often created when the float current level is at a low level. In reality, that low charge current may well be high enough to cause serious damage to healthy cells. This leads to reduced battery life and increased operating cost.

The effectiveness of string equalization in achieving cell balancing has been investigated by many. The results of these studies clearly show that string equalization can easily cause some cells to be overcharged forcing them into gassing while others remain undercharged. Even after the termination of equalization charging, many cells remain undercharged. The studies verify the inability of string equalization to ensure that all cells within the string are equally charged. In addition, infrequent or very frequent string equalization leads to battery degradation due to either sulfation or overcharging or gassing of good cells.

III. Impact of Equalization Voltage

The level of the equalization voltage greatly impacts the life of the battery cells. During charging, when the charging current applied to the cell reaches a certain level, the positive and negative plates begin to become polarized relative to their open circuit potentials. The polarization does not occur immediately because the initial current goes to replace the current lost to self-discharge.

These polarizations cause the voltage of the cell to rise such that it is equal to the cell's open circuit voltage (OCV) plus the positive and negative polarization levels. In VRLA, at low charging currents, the positive plate polarization (PPP) is more dominant than the negative plate polarization. Figure 2 shows the cell polarization of a VRLA battery.

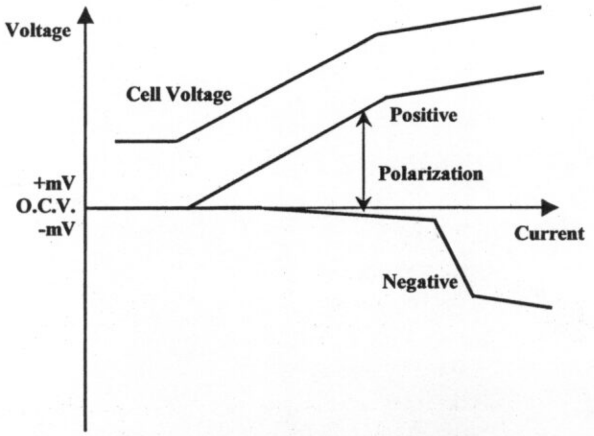

Figure 2: Cell polarization in a VRLA battery

The discussion of positive plate polarization (PPP) is necessary to understand the effects of equalization/float voltage on battery life. The reason that PPP is important is that it has a direct impact on positive grid corrosion. Figure 3 shows the correlation between PPP and a "grid corrosion rate acceleration factor" which is a measure of how fast the grid will corrode relative to an optimal PPP level, which has a factor of 1.0. The corrosion acceleration factors were derived from J. J. Lander's research at the US Naval Research Center during the period between 1951-1956.

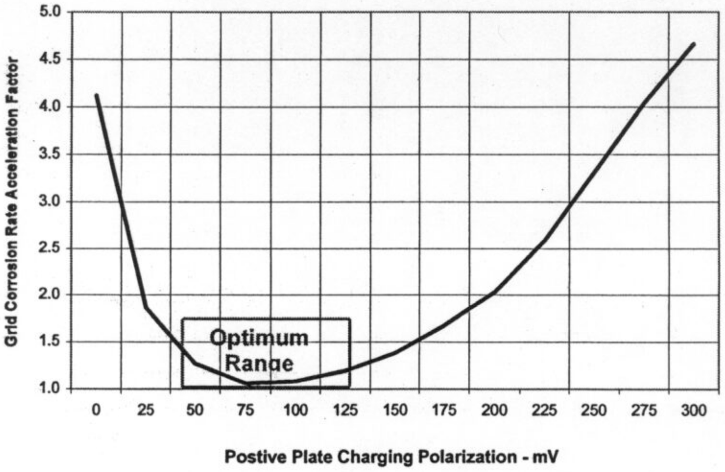

Figure 3: Corrosion rate acceleration factor versus PPP

Figure 3 shows that the higher the PPP, the faster is the positive grid corrosion. There exists an optimal range of PPP where the corrosion acceleration rates are close to unity, namely, 50-120 mV.

The PPP is directly related to the level of equalization/float voltage. The higher the float voltage, the higher the PPP, the faster the corrosion rate. Figure 4 shows the PPP as a function of the equalization/float voltage at various temperatures.

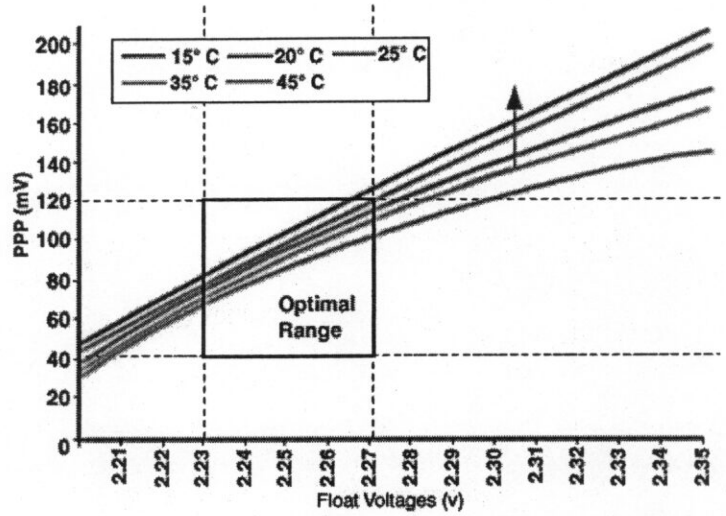

Figure 4: Positive plate polarization (PPP) as a function equalization/float voltage

As shown in Figure 4, maintaining an optimal PPP dictates the application of low equalization/float voltage in the range of 2.23 – 2.27 volts per cell (VPC). The application of elevated per cell voltages during equalization and float charging, typically in the range of 2.3-2.6 VPC, clearly results in higher levels of PPP (in excess of 150 mV) and would thus result in more than doubling the corrosion rate.

The reduction in cell life due to elevated cell voltages during equalization and float charging can be plotted as a function of the applied cell voltage as shown in Figure 4. Elevating cell voltages beyond 2.3 VPC can result in more than 40% reduction in battery life. In practice, equalization is achieved using much higher cell voltages, namely 2.4-2.6 VPC. It can be clearly seen from Figure 5 that the reduction in cell life can exceed 80%. This is a significant penalty that many battery users fail to recognize.

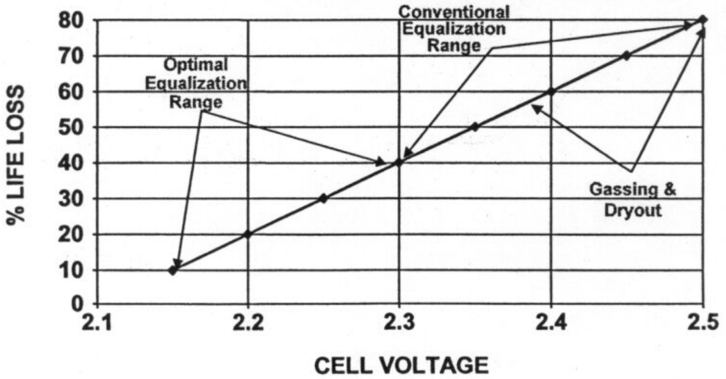

Figure 5: Reduction in cell life at elevated cell voltages

IV. Individual Battery Equalization

In order to prevent the adverse effects of improper charging of battery modules, individual modules need to be maintained at an equalized charge level. The property of individual cell voltages possessing the same value once they have reached the final state of charge can be utilized to achieve this task.

One technique that has been widely used to circumvent the negative impacts of string equalization is individual cell balancing using shunt regulators. Shunt regulator devices are used across each cell to bypass charge current when the battery voltage exceeds a preset level. The basic structure of a shunt regulator consists of a resistive element, a switching device along with some control circuitry. The switching device is controlled to bypass a preset level of current when the cell voltage exceeds a certain limit. The bypassed energy is dissipated as heat within the resistive element. Although this technique is somewhat effective in limiting gassing or overcharging of good cells, it has many drawbacks.

1. The amount of current bypassed is quite limited since all the energy is dissipated as heat in the resistive element. Hence, the bypass current capability is limited to only 100-200mA.
2. Shunt regulators are only effective during overcharge periods. Hence, cells are still subjected to high voltages, thus accelerating grid corrosion rates and reducing battery life. In addition, no balancing is accomplished during discharge and idle modes.

Other active battery equalization schemes have been proposed that utilize more efficient bypass circuitry, which shunts the charging current around overcharged cells to other cells within the string. However, most of these approaches utilize dedicated DC-to-DC converters and/or include multi-winding transformer structures thus making it harder to modularize for different battery strings and bus voltages. The need for a modular, easily configurable and highly efficient battery equalizer is paramount.

A new scheme, which utilizes modular non-dissipative charge equalization modules, has been developed by PowerDesigners. PowerCheq™ is a bidirectional charge equalization device that is connected across pairs of batteries within a string (Fig. 6). A battery string with N batteries requires N-1 PowerCheq™ modules (Fig. 7). The PowerCheq™ modules interconnect batteries in a series string creating a bidirectional charge transfer path between neighboring batteries and enabling the entire battery string to be equalized. Bi-directional equalization ensures that all batteries in a string are equalized no matter where the low voltage battery is located.

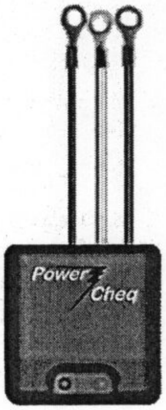

Figure 6: The new PowerCheq™ module

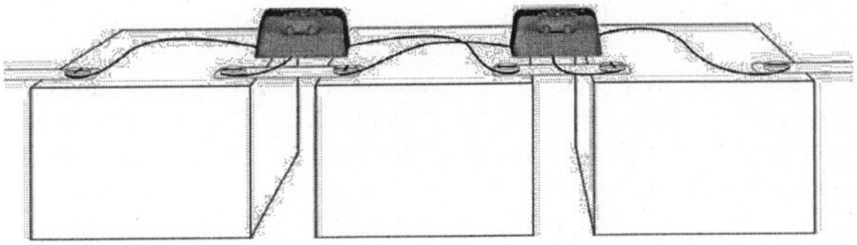

Figure 7: Staggering PowerCheq™ modules across a battery string

V. Experimental Verification

In many stationary battery strings, a single battery failure may result in the whole battery string getting replaced. This represents a significant cost penalty to end-users, as many of the remaining batteries may still be healthy. The tendency would then be to replace the failed battery with a new one. This may cause further operational and performance problems due to the mismatch in health and capacity between the new and old batteries. Individual battery equalization can thus help equalize the string by transferring energy from the new battery to the rest of the string.

In order to verify the performance of individual battery equalization on battery performance and life, an experimental study was conducted. The tests performed simulated a stationary battery application. In order to test the performance limits of individual battery equalization, two strings of three batteries were assembled with each having two old battery modules and a new one. The 36V battery packs consisted of 12V, 50Ahrs sealed lead-acid batteries. The old batteries have been used in the field in a similar stationary application. A used and a new battery were available as spares in case of premature battery failures. For the purposes of this test, the capacity C of the batteries will be defined at the 8-hour rate, namely 45.2 Ah.

The batteries will be tested in a shallow discharge cycling regime similar to that encountered in float service such as telecom or cable TV backup battery. The string without the PowerCheq modules will be periodically boost charged for equalization, and the capacities of all strings will be periodically measured for comparison.

Initial Conditioning

For initial conditioning of the battery packs, and since the state of charge of the old batteries is unknown, the batteries were first fully charged at a constant current of 20A to a voltage of 41.4V (2.3 VPC). The batteries were then discharged at the C/8 rate (5.65 A) down to 31.5V (1.75 VPC). There will be no equalization or boost charge performed.

Shallow Discharge Cycles

Starting with a full charge, the strings will be discharged at the C rate (45.2 A) for 12 minutes, using 20% of the nominal string capacity. After a one-minute rest, the strings will then be recharged at 41.4 V at the C/8 rate (5.65 A) for 156 minutes. The cycle will then be repeated, for 100 shallow discharge cycles. A capacity test will then be performed. After each 100 shallow discharge cycles, a test will be made of the string capacities. The strings will be discharged at a C/8 rate to 31.5 V. The strings will be recharged with the total charge return of 110%.

Test Setup Description

The Power Battery Inc. PRC-1250 Sealed Lead Acid battery used in this study has a rated capacity 45.2 Amp-hours (Ah) at a C/8 discharge rate with a nominal voltage is 12 Volts. The battery modules were configured into two separate series connected strings with each string consisting of 3 battery modules, two old and one new, and a nominal capacity of 36 Volts. A battery monitoring system was used to log the individual battery voltages and temperatures in both strings during testing. The battery equalization devices were installed on one battery string as described earlier. Under all operating conditions, the ambient temperature of the operating environment in which the test is being conducted will be maintained between 65°F and 75°F.

Test Results

The battery strings were cycled according to the above-described shallow discharge regime. Figure 8 shows the battery voltages of the string with no equalizers during the initial shallow discharge cycles. The new battery (Mod 3) shows relatively higher operational voltages during the charge and discharge cycles. In addition, the difference in battery voltages is quite evident, as the old batteries would tend to be less efficient during charge and discharge.

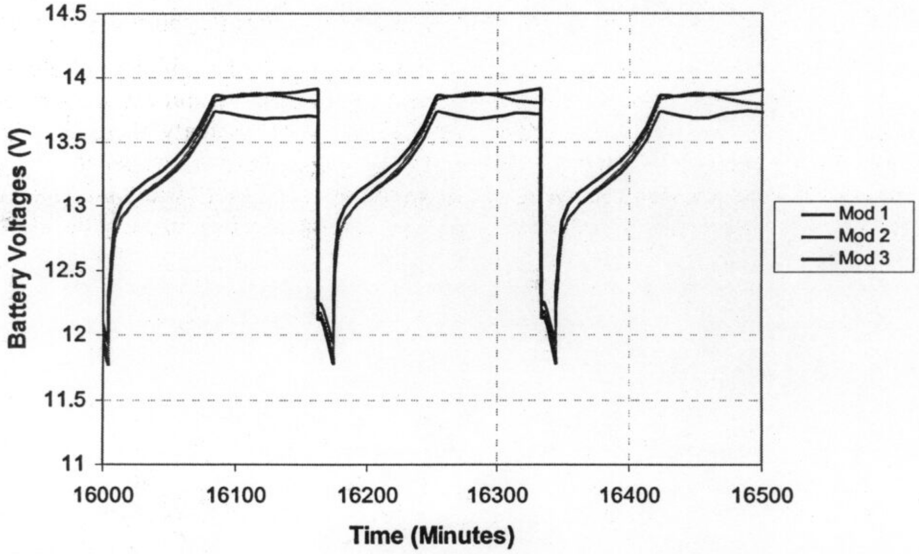

Figure 8: Battery voltages during the initial shallow discharge cycles for the string without equalizers

The battery string with equalizers showed improved operational characteristics as shown in Fig. 9. It is even hard to distinguish the new battery (Mod 3) from the old ones as the battery equalizers tend to balance the voltages by moving energy from the new battery to the other batteries within the string. This will allow all batteries to be properly charged and discharged, thus maximizing the energy output during discharges.

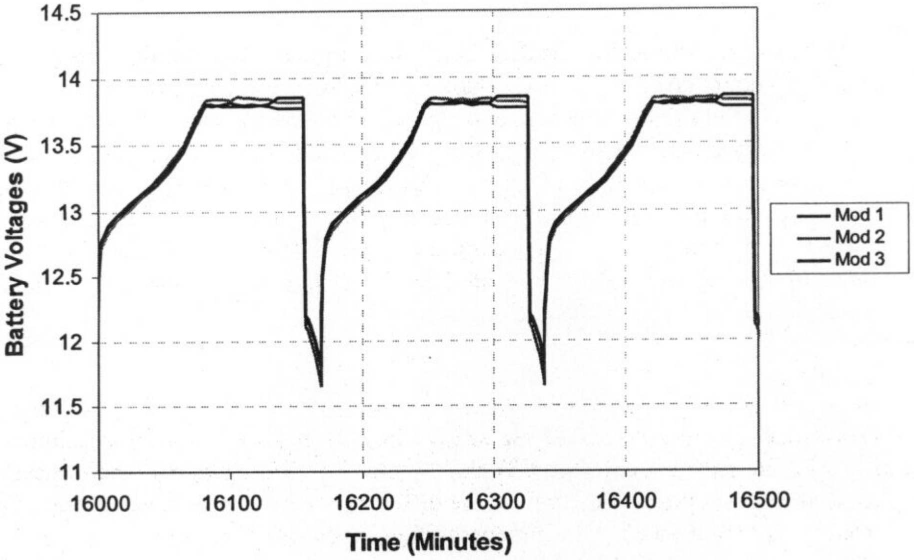

Figure 9: Battery voltages during the initial shallow discharge cycles for the string with equalizers

The situation got worse for the string without equalizers during the last shallow discharge cycles as shown in Fig. 10. The variation in battery voltages is quite large and the amount of energy output has degraded as one the old batteries (Mod 1) does not get properly charged. This can be clearly seen by observing the battery voltages during the capacity tests performed after the termination of the shallow discharge cycles as shown in Fig. 11. Since battery module 1 does not get properly charged, its voltage dips quite low during the capacity discharge test thus limiting the amount of energy available from the string.

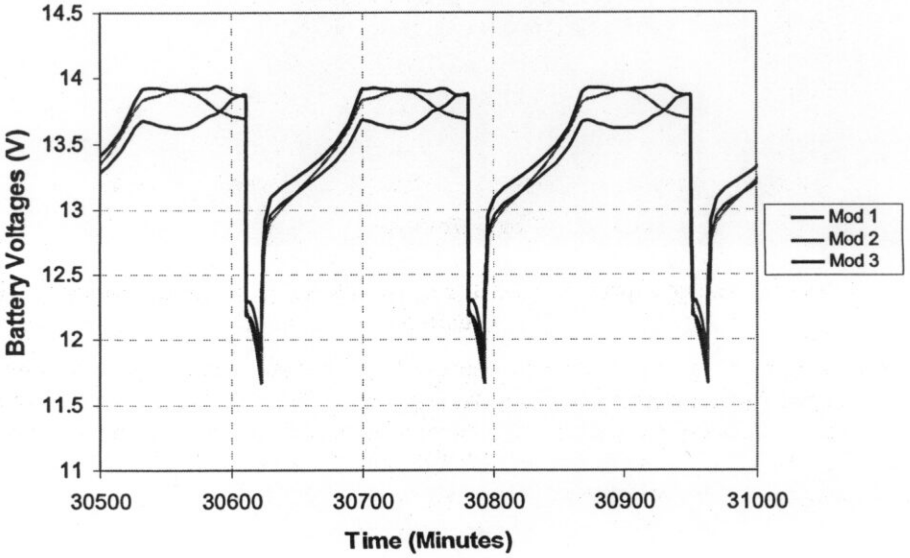

Figure 10: Battery voltages during the final shallow discharge cycles for the string without equalizers

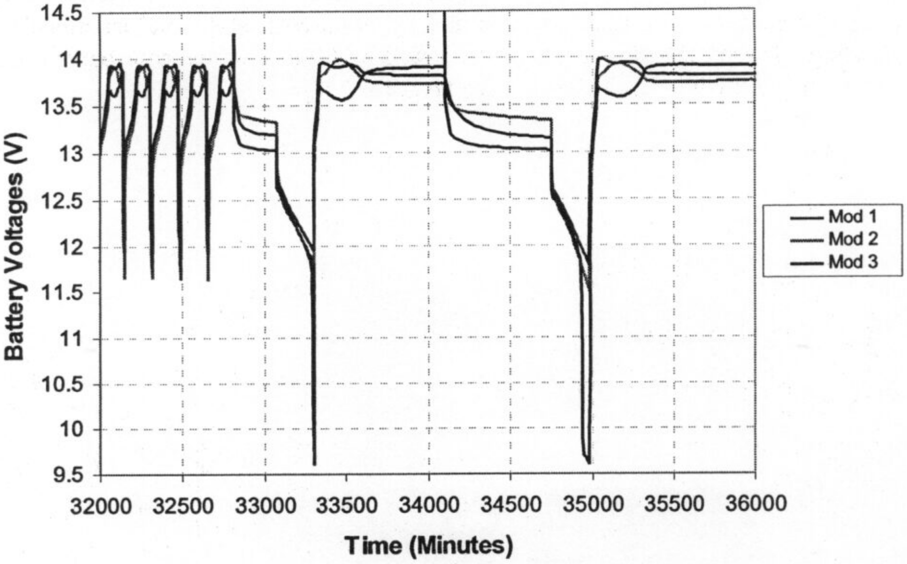

Figure 11: Battery voltages during the final shallow discharge and capacity charge/discharge cycles for the string without equalizers

The above problems were mitigated for the battery string with equalizers, as the equalizers will always shuffle energy between the individual modules to minimize load and voltage imbalances. Figure 12 shows the battery voltages during the last shallow discharge cycles while Figure 13 shows the battery voltages during the capacity tests performed after the termination of the shallow discharge cycles. It can be clearly seen that the battery voltage differences are minimal and the batteries' performance is quite similar.

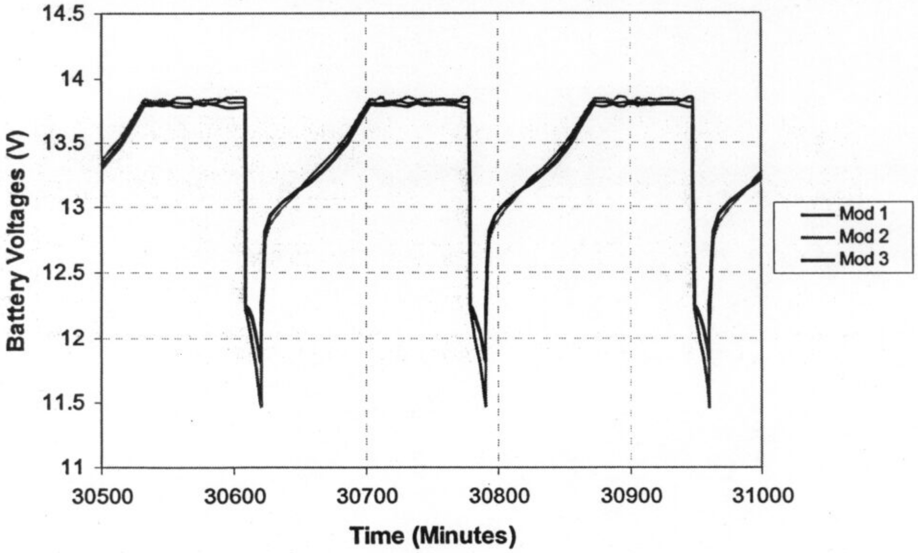

Figure 12: Battery voltages during the final shallow discharge cycles for the string with equalizers

During the final capacity tests, no capacity degradation is observed as the equalizers will act to balance the load between the new and old batteries thus preventing the old batteries from getting deeply discharged. In addition, the equalizers will also prevent the new battery from being overcharged while allowing the old batteries to be fully charged.

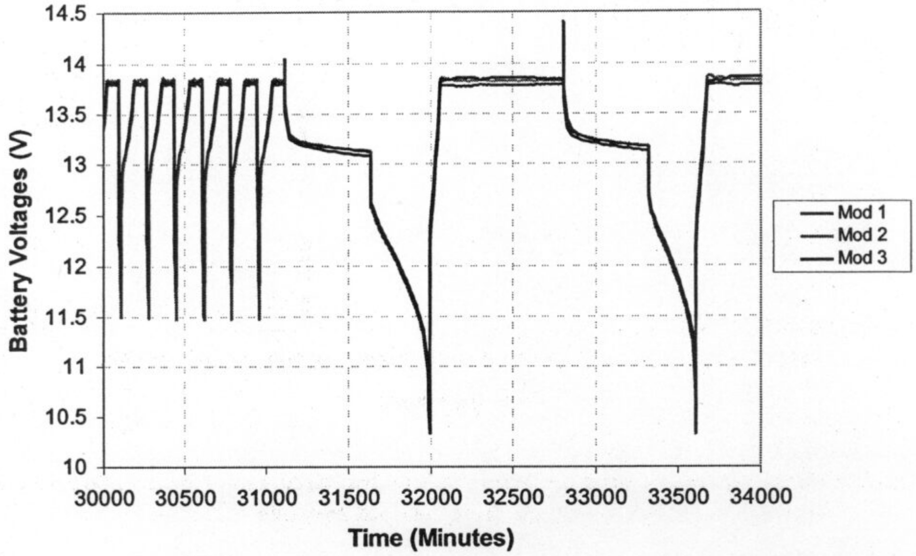

Figure 13: Battery voltages during the final shallow discharge and capacity charge/discharge cycles for the string with equalizers

Table 1 summarizes the capacity test results for the two battery strings. The capacity of the battery string equipped with equalizers (String 1) degraded by 5.4% after 100 shallow discharge cycles. On the other hand, the capacity of the string with no equalizers degraded significantly by 23.4%. This was mainly due to the degradation of one of the old battery modules where the battery voltage dipped to 9.6V during the capacity discharge test.

Table 1: Capacity tests for both battery strings

Test Cycle #	Ah Out		Minimum Battery Voltage (V)	
	String 1	String 2	String 1	String 2
10	100 %	100 %	10.3 V	10.3 V
110	95.6 %	76.4 %	10.3 V	9.6 V
% Degradation	5.4 %	23.6 %	-	-

Note: String 1 was equipped with PowerCheq charge equalizers.

VI. Conclusion

Conventional string equalization has been shown to be ineffective in equalizing battery strings as it leads to gassing of good cells and increases the positive plate corrosion rate due to the high positive plate polarization (PPP) thus reducing battery life and performance. Although shunt regulators have been widely used to alleviate the negative impacts of overcharging and gassing, NOW

they are also ineffective as they still subject cells to high voltage levels and may mask high resistance cells.

Individual Battery Equalization is the only effective means of achieving true equalization. The main advantages of utilizing individual battery equalizers include:

- Maintaining cells/modules at the same charge level
- Eliminating the need for equalization charging and thus reducing cell voltages during charging
- Reducing the positive plate polarization (PPP) and thus reducing positive grid corrosion
- Improving battery capacity and life while reducing operating costs

The impact of individual battery equalization on the performance of VRLA batteries in stationary power applications has been verified. Shallow discharge cycle tests were performed on two similar battery strings with each consisting of two old batteries and a new one. One of the strings was equipped with PowerCheqs, a new line of individual battery equalizers. The battery string equipped with the equalizers showed significant improvements in energy output and capacity compared with the other string. This was due to the operation of the battery equalizers as they offer a real-time equalization function that maintains batteries balanced during charge, discharge, and while sitting idle. During charge, the equalizers prevent the new battery from being overcharged while allowing the old batteries to be fully charged. During discharge, the equalizers act to balance the load between the new and old batteries thus preventing the old batteries from getting deeply discharged. The net result is a significant improvement in battery life and performance.

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Abstract

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Experiences with Individual Cell Equalizers ability to prevent,diagnose, and correct common battery conditions, 1988-1995

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Abstract

This paper identifies beliefs and misconceptions relating to the operation and testing of stationary battery banks, and the problems they present to the battery user. These problems cost millions due to the inability to prevent, diagnose; and/or correct common battery conditions. This paper also identifies how BWB Battery Corp. Ltd. has used the Individual Cell Equalizer (ICE), designed and patented by Ericsson Communications Inc., Stockholm, Sweden to prevent and correct these problems. The first installation of ICE by BWB was in 1988. Since then, we have had the opportunity to identify and study the advantages of this unique device. It has been used as a tool for maintenance, testing, and the prevention of known inherent battery conditions. ICE has provided substantial savings in all aspects of maintenance and testing. Using modern maintenance techniques that have been developed by BWB to complement the use of ICE, it is now possible to identify defective cells, measure operational life and security of battery banks at a fraction of the traditional cost. Techniques are presented to show evidence that the voltage levels of all cells will now be uniform with little or no voltage variations. Techniques are presented to show evidence that if cells are consuming a normal amount of current with ICE to maintain their set voltage level, they will be found to be within their rated capabilities

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