Copy of Paper Presented to:

intelec 96

Boston, Massachusetts
October 6 - 10, 1996

VRLA Battery Conductance Monitoring

Part V:
Strategies for VRLA Battery Testing and Monitoring in Telecom Operating Environments.

by:
Mark J. Hlavac
Midtronics, Inc., Burr Ridge, Illinois, USA
Dr. David O. Feder
Electrochemical Energy Storage Systems Inc.
Madison, New Jersey, USA

MIDTRONICS

Midtronics, Inc.
8230 S. Madison Street
Burr Ridge, Illinois 60521
U.S.A.
Tel: (630) 323-2800
Fax: (630) 323-2844

Midtronics b.v.
Noord IJsseldijk 24
3402 PH - IJsselstein
The Netherlands
Tel: +31 306 873 100
Fax: +31 306 889 015

18th International
Telecommunications
Energy Conference

VRLA Battery Conductance Monitoring

Part V: Strategies For VRLA Battery Testing and Monitoring in Telecom Operating Environments.

Mark J. Hlavac, Midtronics Inc.
Dr. David Feder, Electrochemical Energy Storage Systems Inc.

Abstract

Using actual VLRA battery field data from a telecom transmission office, this paper examines the accuracy and cost effectiveness of midpoint voltage (MPV) monitoring techniques vs. conductance measuring techniques based on both single and multicell units. Results indicate the inability of several midpoint voltage techniques to identify low capacity cells, contrasted with the high accuracy of the several conductance techniques, including a new midpoint conductance concept. The paper demonstrates how these conductance results may be utilized to optimize cell replacement for maximum capacity improvement within fixed budgetary constraints.

Introduction

In the telco environment of the 90's where cost cutting and down sizing have become widespread, cost-effective battery system management is high priority. While a regular battery management program will ultimately reduce down time, improve customer service and system quality, programs to add capital equipment can only be justified if a reduction in costs can be expected through improved priority management or because of added value associated with more reliable service.

Typical telco environments include a budgeting process at the end of each year. One of the budget items is battery replacement. Down sizing may have reduced their resources to test the batteries they have. This creates a three part dilemma:

1. Without resources, they are unable to test and determine which cells or batteries should be replaced.
2. They may be forced to adopt time-based replacement of cells or battery strings which may still have good capacity.
3. At the same time, they may be unaware of possible reserve loss, potential customer service interruption and significant revenue loss.

This stimulates the search for more cost effective-solutions which will help to optimize the management of battery replacement.

This paper compares the accuracy and cost effectiveness of several possible solutions. Using actual field data, it compares midpoint voltage monitoring techniques vs. a stationary monitoring system using conductance measuring techniques on a single cell, multicell and midpoint basis.

The result of the conductance analysis presents a cost benefit analysis to the problem. This approach includes the following elements; a conductance audit of the entire system; a cost benefit analysis of replacing only the cells with the most serious capacity loss based on a budget approach; a priority system which optimizes battery reserve and minimizes battery replacement cost.

Monitoring Techniques

In order to evaluate the accuracy and utility of several monitoring techniques, the authors have utilized actual test data on five -48v strings of 1000 AH VRLA AGM cells, from a telecom transmission office. The cells were approximately 5 to 6 years old, in full float service, when tested. The data available includes individual cell float voltages, individual cell conductance measurements and complete discharge data on each of the 120 cells which were discharged at the two hour rate to 1.88 volts per cell (a small portion of these data has been previously been published in INTELEC 1993, Figs. 12, 13 & 14, page 379). The data used for each string in the following analysis are shown in the tables of appendix A.

Midpoint Voltage Method

In this technique, the 24 cell string is measured in two sections, cells 1 to 12 and cells 13 to 24. The total voltages of each half are compared and if they differ by more than a previously determined amount[6], the MPV monitoring systems are intended to indicate possible difficulty and/or provide an alarm.

As a prelude to our analysis, we should emphasize the results of an earlier study[1], in which we clearly demonstrated that in strings in which cell capacity results varied from 0% to 100%, all float voltages were within the manufacturer's recommended acceptable float voltage tolerances.

For the five strings involved in this analysis, Table 1 shows the 12 cell float voltage totals for cells 1 to 12 vs. 13 to 24; the voltage differences, cells 13 to 24 minus cells 1 to 12; the ratios of totals, cells 13 to 24/cells 1 to 12, and similar data for the measured capacity values for each half string. As an additional exercise, to test the sensitivity and accuracy of the midpoint float voltage and other techniques, we rearranged the cells in string 5, putting all the high capacity cells in the 1 to 12 cell group and all the low capacity cells in the 13 to 24 cell group. This resulted in an average capacity of 84.3% for cells 1 to 12 vs. 48.7% for cells 13 to 24. The analysis which follows will include the results from this rearranged string.

Reviewing the midpoint voltage differences, we see that they range from -0.07 volts. to +0.06 volts, while capacity differences range from -35.6% to +10.9% of the manufacturer's published capacity. To get a better perspective, the capacity differences were plotted vs. the midpoint voltage differences shown in figure 1. A regression analysis indicates a correlation coefficient, $R^2 = 0.118$, i.e., essentially no correlation between midpoint voltage differences and midpoint capacity differences. Note that even in the rearranged string 5, where the capacity difference is (48.7% minus 84.3%) equal to -35.6%, the midpoint float voltage difference is only -0.02 volts (27.07 - 27.09).

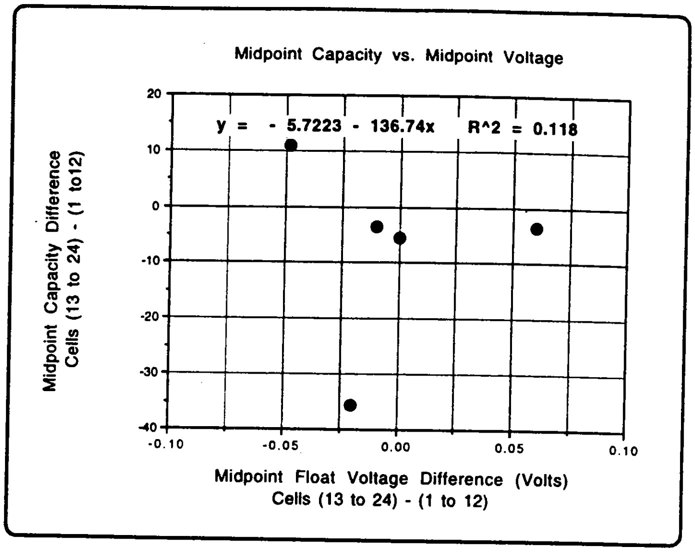

Figure 1

Since these actual cell data do not support the effectiveness of midpoint voltage monitoring as a indicator of a capacity problems, it seemed worthwhile to consider some calculated scenarios in which it might be more applicable. Information from manufacturers and national and international standards suggest that once stabilized and floating properly, VRLA cell voltages may vary by ± 2 .5%. For a string floating at 2.25 volts per cell (VPC) average, this allows a variation of ± 0.056 volts. Hence, cells could float as low as 2.19 volts and as high as 2.306 volts and still remain within acceptable limits. If we were to take a best (or worst) case example, putting all the low cells in 1 to 12 and all the high ones in 13 to 24, would result in (12 x 2.306 = 27.672) minus (12 x 2.19 = 26.28). The MPV is 27.672 minus 26.28 which equals a 1.392 voltage difference between the two portions of the string. Since some users have considered a MPV differential of 1.0 volt as an alarm indicator[6], these results suggest that cells floating within the manufacturer's published tolerances could cause a false alarm.

Some users[6] have suggested that the MPV technique, while not useful in detecting capacity problems, could detect shorted cells. Again, let us examine some calculated possibilities:

In most actual situations, shorted cells float at approximately open circuit values for extended periods. For a 1.300 specific gravity (SG) absorbed glass mat VRLA cell, this means 2.15 volts, on float, would indicate a probable short. If one accepts the 1.0 volt midpoint voltage difference as appropriate for an alarm, it is a simple calculation to determine the number of shorted cells, which must all be in the same half of the string, to produce a one volt difference. For a string floating at 2.25 volts per cell average, 8 shorted cells at 2.15 volts, would leave the remaining 16 cells at 2.30 volts. If all eight cells were in the 1 to 12 cell half, then the voltage of cells 1 to 12 would be 26.4 volts vs. the voltage of cells 13 to 24 at 27.6 volts, for MPV difference of 1.2 volts.

Ignoring the statistical improbability involved, note that the sensitivity of the midpoint voltage changes with the overall string float voltage. For a string floating at 2.27 volts, six shorted cells, at 2.15 volts per cell would produce a midpoint voltage difference of 0.96 volts. For a string floating at 2.35 volts per cell, four shorted cells would produce a voltage difference of 0.96 volts. Hence, the sensitivity to normal shorted cells of midpoint voltage is poor, requires multiple shorts in the same portion of the string and is a function of the overall string float voltage setting.

Another possibility is a shorted cell at the unusually low float voltage of 1.95 volts. This would result in a MPV difference of

Table 1
Midpoint Voltage and Midpoint Capacity Data.

	String 1	String 2	String 3	String 4	String 5	String 5 (Reconfig)
Voltage 1-12	26.806	26.880	27.010	27.070	27.080	27.090
Voltage 13-24	26.758	26.810	27.070	27.060	27.080	27.070
Midpoint Voltage Difference	-0.048	-0.070	0.060	-0.010	0.000	-0.020
Midpoint Voltage Ratio	0.998	0.997	1.002	0.999	1.000	0.999
% Capacity 1-12	28.7%	19.1%	30.4%	56.7%	69.4%	84.3%
% Capacity 13-24	39.6%	34.1%	26.8%	53.2%	63.9%	48.7%
Midpoint Capacity Difference	10.9%	15.0%	-3.6%	-3.5%	-5.5%	-35.6%
Midpoint Capacity Ratio	1.380	1.790	0.882	0.940	0.920	0.578

only 0.32 volts, for a single shorted cell. It would require 3 cells at 1.95 volts, all in the same group to produce a MPV difference of 1.03 volts. Since a 1.95 volt shorted cell is rare, three in the same group is highly unlikely. A much less likely condition is a shorted cell at 1.0 volts, which would result in a midpoint voltage difference of 1.29 volts and cause an alarm, but again as with the 1.95 volt short, a 1.0 volt short is extremely unlikely. Some experts[7] have proposed the possibility of an "ideal" short, i.e., a cell at zero volts. Here the calculation results in a midpoint voltage differential of 2.34 volts, well above alarm conditions, but so unlikely as to make its detection of no practical use.

The result of these analyses, both on real cells with both float voltage and actual capacity values and of hypothetical values in theoretical exercises, using different values of voltages for shorted cells all indicate that midpoint voltage is essentially useless as a fault detector, except in the most unlikely circumstances.

Midpoint Voltage Monitoring During Discharge

In a paper presented at INTELEC '94, Heron et al[6] proposed midpoint voltage difference monitoring during discharge, with the expectation that the voltage of the lower capacity half, would deviate rapidly from the voltage of the stronger half. They chose a MPV alarm target of ± 0.5 volts as an indicator of low capacity and plotted MPV vs. discharge time. Their data show a significant increase in MPV as the discharge proceeded. However, careful analysis of their data (pp 502-503, reference[6]) shows that in all cases a significant percentage of the overall discharge must occur (44% to 88%) before the MPV value reached the ± 0.5 volt alarm point, thus causing doubt that the technique could provide definitive results with only a brief portion of the discharge required.

For this paper, the data of string #5 have been utilized to produce figure 2. Figure 2 shows the battery string voltage vs. time plot and the MPV difference vs. time. Note that the battery reached its 45.12 volt (1.88 VPC) cutoff voltage in only 80 minutes, i.e. 66% of rated capacity value. The MPV difference didn't reach the intended ±0.5 volt alarm target until 135 minutes, 55 minutes after the string had already failed.

In order to test the discharge MPV technique under idealized conditions, the re-configured string #5 data was then plotted, as in figure 3. Despite the midpoint capacity difference of 84% vs. 48% between the two half strings, it still required 35 minutes of discharge time before the MPV value reached the ± 0.5 volt MPV alarm target. This is 44% of the total discharge time, even under the most exaggerated capacity difference between the two halves of string #5. Based on these data, plus the data shown in the INTELEC '94 paper, it is clear that a significant percentage of the discharge must be performed before the MPV alarm target is reached. This raises serious questions as to any time or cost savings which would result from the use of this technique as a battery monitoring device.

Conductance Monitoring

To build a basis for justification of deploying a battery monitoring system, a profile of the costs associated with that deployment must be compared to the resulting improved level of service protection. The most important criterion associated with deploying any battery monitoring system would be to identify the demonstrated level of accuracy associated with the various testing techniques. Included in this report are several models which suggest the user can select from a wide variety of options available such as single or multiple cell on-line conductance monitoring as well as single or multiple cell on-line conductance testing using portable test equipment. The expected cost associated with the monitoring approach and the respective accuracy of each technique will be evaluated using conductance and capacity data for five strings shown in appendix A. In this assessment, the authors use individual cell conductance and capacity data to synthesize equivalent conductance for 3 cell, 6 cell, and 12 cell groups. The average capacity for these same equivalent cell groups are then used to assess and contrast the benefits of multiple cell monitoring.

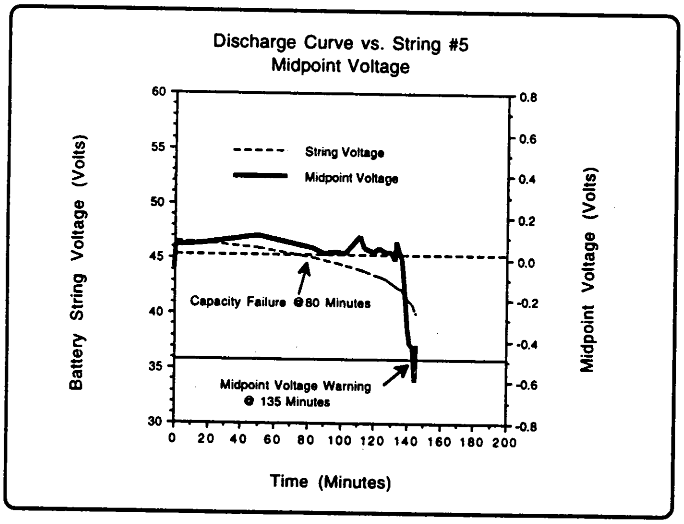

Figure 2

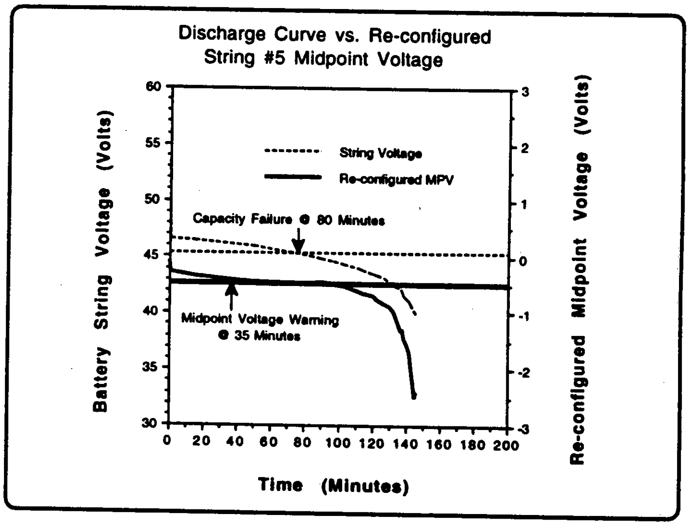

Figure 3

Midpoint Conductance Ratio Method; A New Concept:

In Table 2, we have listed the equivalent midpoint conductance values for cells 1 to 12 and cells 13 to 24 for the same five strings as in Table 1, as well as for the re-configured string #5. The table also lists the 12 cell conductance differences and conductance ratios. In addition, it lists the capacity differences and capacity ratios for each of the 12 cell groupings in each string.

Figure 4 shows a plot of midpoint capacity difference vs. midpoint conductance difference of all of the strings, including the re-configured string #5. The correlation coefficient $R^2 = 0.855$ indicates a strong correlation of midpoint capacity difference with midpoint conductance difference, especially when contrasted with the $R^2 = 0.118$ value of the equivalent capacity/MPV regression. Figure 5 shows a plot and regression analysis of midpoint capacity ratio vs. midpoint conductance ratio, with a correlation coefficient $R^2 = 0.834$, again good correlation, far better than with MPV. Therefore, by either method chosen, midpoint conductance techniques correlate far more strongly with midpoint capacity, than MPV and should therefore be far more useful as a monitoring technique. A high degree of correlation of midpoint conductance with midpoint capacity once again indicates the usefulness of midpoint conductance monitoring to predict cell state of health, without actually having to perform a discharge test. This avoids significant costs, scheduling difficulties and down time associated with performing capacity discharge testing.

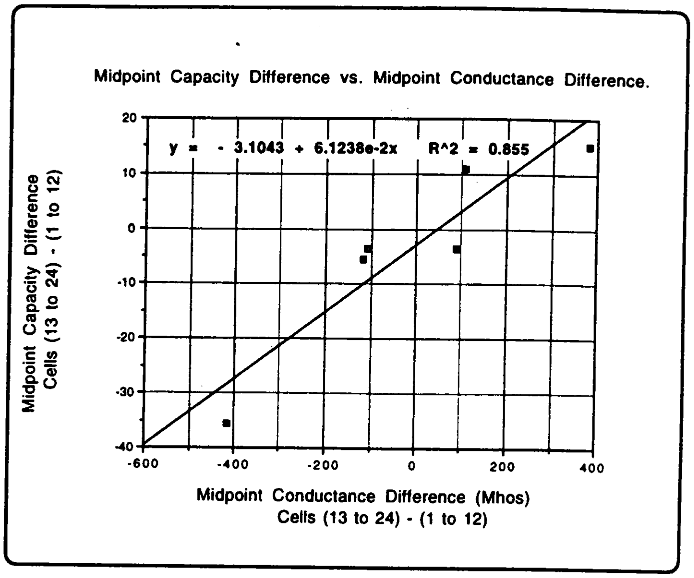

Figure 4

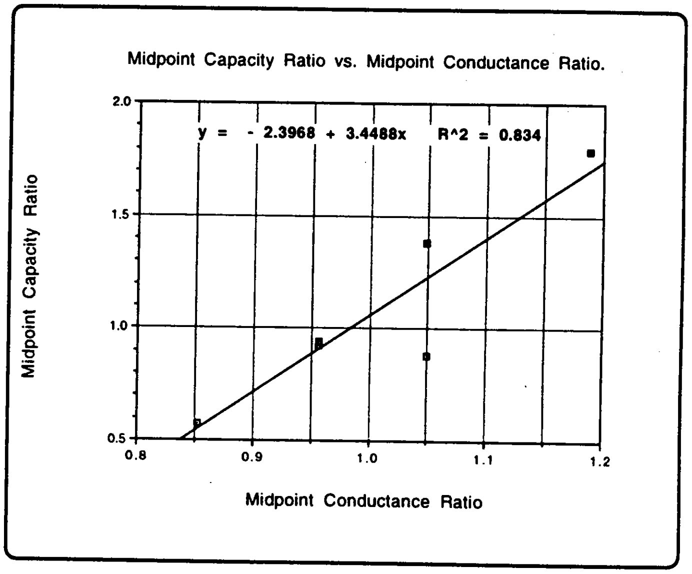

Figure 5

Accuracy/Cost Optimization by Conductance/Capacity Analysis:

In order to determine the absolute accuracy of conductance monitoring techniques, each of the five strings was analyzed on a cell by cell capacity/conductance basis. The results were subjected to regression analysis, the 80% pass/fail values of conductance calculated and each string analyzed cell by cell to determine the accuracy of the conductance value in predicting cell pass/fail results, using the box score technique of previous publications [2,3,4,5].

From these data, the single cell accuracy determinations were made, i.e.: what percent of good plus bad cells were correctly

Table 2
Midpoint Conductance and Midpoint Capacity Data.

	String 1	String 2	String 3	String 4	String 5	String 5 (Reconfig)
Conductance (KMhos) 1-12	2.222	2.026	1.971	2.471	2.640	2.801
Conductance (KMhos) 13-24	2.329	2.407	2.061	2.365	2.523	2.386
Midpoint Conductance Difference	0.107	0.381	0.090	-0.106	-0.117	-0.415
Midpoint Conductance Ratio	1.048	1.188	1.050	0.957	0.956	0.852
% Capacity 1-12	28.7%	19.1%	30.4%	56.7%	69.4%	84.3%
% Capacity 13-24	39.6%	34.1%	26.8%	53.2%	63.9%	48.7%
Midpoint Capacity Difference	10.9%	15.0%	-3.6%	-3.5%	-5.5%	-35.6%
Midpoint Capacity Ratio	1.380	1.790	0.882	0.940	0.920	0.578

identified; what percent of bad cells were correctly identified; what percent of bad cells were missed and incorrectly called good; and what percent of good cells were incorrectly called bad by the conductance measurements.

Figure 6 shows an overall correlation plot of single cell percent capacity vs. single cell conductance, the R^2 value of 0.801 indicating good correlation overall. As in previous publications[2,3,4,5], the intersection of 80% capacity with the regression line was calculated, in order to determine the equivalent conductance value and establish the box score coordinates. For single cells, the plot shows an overall accuracy (good called good plus bad called bad) of 110/120 = 91.7%. Conductance measured two cells as good which were actually at 70% and 79% capacity. It also measured eight cells as bad (9% below the 80% capacity/conductance value) which were actually good. These values are shown in Table 3 in the line entitled single cell.

Figure 7 shows the overall data combined into six cell monobloc conductance and capacity values. Again, regression analysis indicates good correlation, R^2 = 0.853. Figure 7 indicates that, viewed only as six cell monoblocs only one good monobloc (in string 4) is indicated as bad by conductance, while all bad monoblocs are correctly identified by conductance. The reason for the erroneous conductance listing of string 4 can easily be understood, if one returns to the single cell plot (figure 6), where five of the cells listed as bad by conductance are from string 4. The same procedures, used for the other six cell monoblocs results in the overall data of table 3 for six cells, i.e., zero bad cells missed by conductance, 14 good cells erroneously listed as bad by conductance.

A similar correlation plot is shown in figure 8 for the data calculated as 12-cell monoblocs, with an R^2 of 0.708. Figure 8 indicates all twelve cell monoblocs failed both conductance and capacity criteria, with no erroneous monobloc classifications. However, again using string 4 as an example on a single cell basis, the same five cells from string 4 are listed by conductance as bad when in fact they are good when measured as single cells as shown in figure 6. Considering all ten 12 cell monoblocs a total of 14 good cells have been listed as bad by conductance when included in the overall monobloc group. These values are shown on the 12 cell line of table 3. The same procedures were used for each string in blocks of 3 cells, 6 cells and 12 cells and accuracy compared to the actual single cell values. The results are shown in Table 3. Accuracies of conductance in correctly detecting bad cells range from 96% to 100% from single cell through 3 and 6 cell to 12 cell blocks. Overall accuracy of conductance correctly detecting good cells range from 93.3% for single cells to 88.3% for 12 cells blocks. Total overall accuracies, taking all erroneous values into account (good called bad, bad called good) indicate that conductance can accurately detect from 88.3% to 91.7% of cells with both good or bad capacities. Even when used in twelve cell blocks (i.e. a 24 volt monitor), conductance showed an overall accuracy of 88.3% or an overall inaccuracy of 11.7%. It should be noted that the overall inaccuracy of 11.7% was composed entirely of good

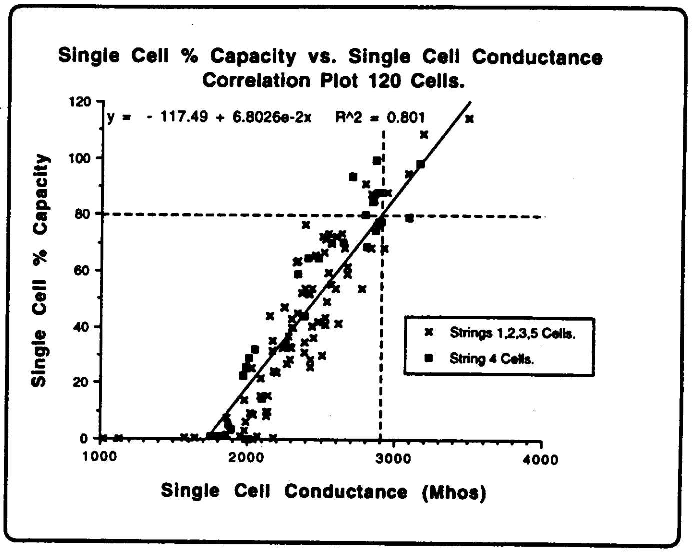

Figure 6

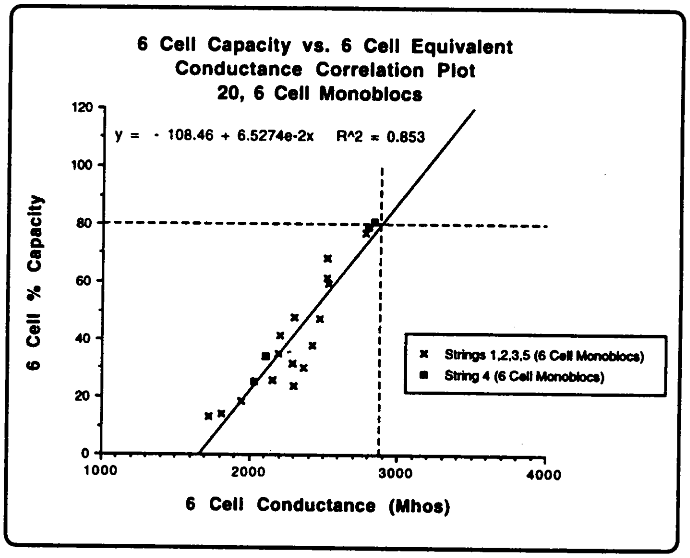

Figure 7

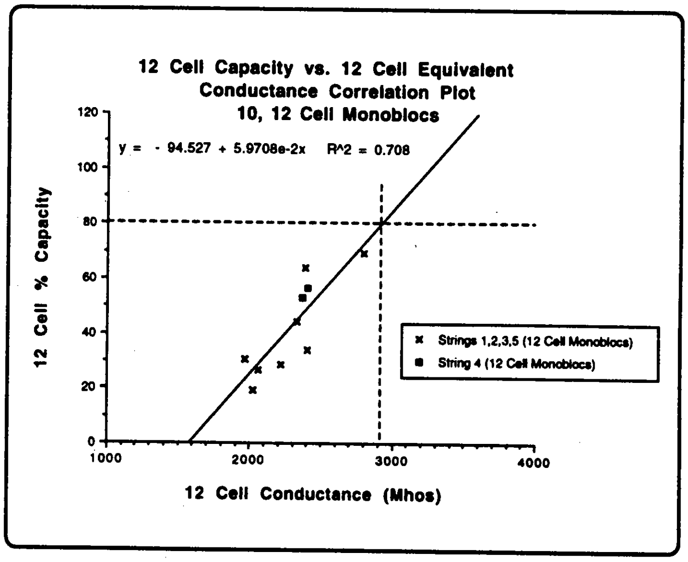

Figure 8

cells called bad. Perhaps more important is that the 12 cell grouping showed 0% bad cells missed using the 6 or 12 cell conductance measurement technique in the overall 120 cell population.

There is no question based on the data shown that the ability to monitor the conductance of individual cells provides the highest level of information and therefore represents the most informative data possible about the condition of the battery. The individual cell resolution understandably increases installation cost and design complexity and therefore the associated monitoring system cost per string is much higher. Conversely, these data demonstrate how a much less complex and less expensive approach for monitoring 6 cell blocks or even 12 cell blocks would provide a more cost effective approach and still maintain a high level of accuracy. When a problem appears as measured by the 6 or 12 cell technique the use of individual cell conductance measurements could be used to more accurately identify cell conditions within the 6 or 12 cell groups. These results for 3, 6, and 12 cell monoblocs are dependent on the actual arrangement of the cells in these strings as found. Therefore the results can not be quantitatively extrapolated to all possible cell/monobloc or string arrangements.

The Battery Plant Audit

In recent years, two of the authors have presented several papers at INTELEC conferences detailing battery failure rates[1,2,3,4]. While this information is beneficial to the industry it should be considered a wake up call to the users of VRLA batteries in hope that remedial actions will be taken to avoid a power system catastrophe. The first step, the battery plant conductance audit, should be performed to assess the battery population conditions for the user. A focus on potentially high risk areas, assessment of temperature controlled battery installations, four to seven years of age would be the suggested area to start since failure rates begin to increase dramatically at this age[5]. For uncontrolled environment telecom battery installations in warmer geographic areas, 18 months to 3 years could be considered high risk. Finally, for battery installations less than 18 months, infant mortality cases indicative of probable manufacturing defects could be identified during the conductance auditing process. Identification and removal of infant mortality cells or batteries would allow for future success of the remaining battery, while taking advantage of the particular warranty situation, and maintain system reliability. Equipment which is commercially available for quickly measuring the internal conductance of battery cells has been used to assess the condition of 5 battery strings in a single telephone office. It has been estimated by one user that a 24 cell string can be completely conductance tested in approximately 30 minutes. In the 5 string battery audit presented, the actual data collection for the five strings could be done in much less than a day. The value of the audit data is extremely high since it forms the framework for a managed approach to an improved battery testing or monitoring program. Other significant factors such as battery age, and number of predicted cell or battery failures for the individual string or strings are also considered as criteria for determination of economic battery replacement and disposition.

Battery Replacement Within Budget Constraints

In every telco, a budget exercise is performed each year, and funds are set aside for battery replacement. These funds can be used for inevitable emergencies, or proactive management can use them to reduce the cause of emergencies. Besides the obvious customer service and revenue loss implications, a proactive management system will actually reduce costs over time because only the most serious problems will be addressed. The cost benefit analysis is accomplished by observing that the replacement of a cell which has 80% capacity costs the same as replacement of a cell which has 30% capacity. The capacity gain per dollar spent in the second case is 3.5 times greater than the first case: (100%-30%)/(100%-80%). Therefore the cost benefit capacity ratio is easily obtained.

Test Case

Let us look at a test case of five single string batteries which have undergone an audit using both conductance tests and capacity tests for validation. The batteries tested are VRLA (valve regulated lead acid) type batteries which are 5 to 6 years in age, 1000 ampere hour capacity as previously described and shown in appendix A. Hypothetical replacement costs for only the cell replacement is estimated at $400 per cell. For this telco, management has allowed a budget of $20,000 for the year for battery replacement. Appendix A shows the conductance readings, discharge capacity and measured float voltage for each of the 120 cells. Based upon the individual string data in appendix A and the normal 80% end-of-life industry-accepted criterion, 107 cells would normally be expected to be replaced. However, the hypothetical budget of $20,000 would only allow for replacement of 50 cells without consideration of other expenses. Regardless of the test method the cells in string #1 and #2 would consume the entire year's budget leaving only 2

Table 3: Overall Accuracy Strings 1-5

	# Bad Missed	% Bad Missed	% Bad Found	# Good Missed	% Good Missed	% Good Found	Overall Inaccuracy	Overall Accuracy
Single Cell	2	1.7%	98.3%	8	6.7%	93.3%	8.3%	91.7%
3 Cell	4	3.3%	96.7%	9	7.5%	92.5%	10.8%	89.2%
6 Cell	0	0.0%	100.0%	14	11.7%	88.3%	11.7%	88.3%
12 Cell	0	0.0%	100.0%	14	11.7%	88.3%	11.7%	88.3%

good cells to replace poor cells in the three remaining strings. In replacing only the cells below 80% for two strings, the net increase in cell capacity would be from 36.5% to 100% for a gain of 63% for string #1 and from 23% to 100% or a gain of 77% for string #2. However, little performance improvement would be obtained in the remaining string 3 and no improvement for strings 4 and 5.

As an alternative approach, if 50 of the poorest performing cells (< 35%) capacity were replaced, not every string would be up to 100% capacity. However, one can see that this approach will maximize the capacity benefit to cost ratio on each of the individual strings. Selection of the 50 poorest performing cells from each of the strings results in an improved capacity benefit of 36.5% to 81.5% for string #1 with 13 cells replaced, 26.7% to 88.2% for string #2 with 16 cells replaced, 28.7% to 81% for string #3 with 14 cells replaced, 54.8 to 80% for string #4 with 7 cells replaced and no cells remaining to apply to string #5 so no improved performance is observed.

Such a simple battery management system can be easily instituted without need for spending beyond the equipment used to perform the conductance audit (approximately $5,000.00), the manpower needed to perform the test, and the cost and time to replace the cells which indicate poor measured conductance or capacity loss. It should be noted that industry rule of thumb indicates replacement costs are approximately equal to the cell cost. Therefore replacement of a $400.00 cell realistically requires a $800.00 per cell overall expense. Therefore the $20,000.00 budget would only allow for replacement of 25 cells (with less than 10% capacity). In our example now only 25 new cells would be available for replacement. This reduces the capacity benefit of the upgraded strings from 36.5% to 52.4% for string #1 with 4 cells replaced, 26.7% to 67.4% for string #2 with 10 cells replaced, 28.7 to 61.3% for string #3 with 8 cells replaced, 54.8% to 67% for string #4 with 3 cells replaced and no change 66.6% to 66.6% for string #5. If the application is critical, or if manpower is in short supply, or the location is remote, a monitoring system can be utilized which will make the tests automatic and continuous, giving the same result, and the same prioritization of replacement urgency.

Conclusions

Using actual field data, this study has determined:

1. Midpoint Voltage (MPV) techniques do not appear generally useful:
   - For detecting low capacity cells.
   - For cells which exhibit the usual type of internal shorts.
   - In discharge testing for detecting a low capacity 12 cell group without requiring a major portion of the discharge to be completed.

2. Midpoint conductance techniques can detect low capacity cells using:
   - Midpoint conductance differences.
   - Midpoint conductance ratios.

3. Conductance techniques can accurately detect 96 to 100% of low capacity cells when measured:
   - As single cells.
   - In three cell groups.
   - In six cell groups.
   - In twelve cell groups.

4. In worst case situations, conductance techniques may correctly identify 88% to 92% of good cells found.

5. Utilizing the ability of conductance testing or monitoring to identify low capacity cells allows the telco to:
   - Determine those with most urgent need for replacement.
   - Prioritize replacement needs commensurate with budget capabilities.
   - Optimize battery reserve without the need to perform costly discharge tests.

References

1. D.O. Feder; T.G. Croda; K.S. Champlin; M.J. Hlavac: "Field and Laboratory Studies to Assess the State-of-Health of Valve Regulated Lead Acid Batteries: Part 1 Conductance/Capacity Correlation Studies." Proceedings of the 1992 INTELEC Conference: pp 218-233.

2. M. J. Hlavac; D.O. Feder; T. G. Croda; K.S. Champlin: "Field and Laboratory Studies to Assess the State-of-Health of Valve-Regulated Lead Acid and Other Battery Technologies: Using Conductance Testing: Part II: Further Conductance/Capacity Correlation Studies". Proceedings of the 1993 INTELEC Conference, Paris , Volume II: pp 375-383.

3. D.O. Feder; M. J. Hlavac; "Analysis and Interpretation of Conductance Measurements Used To Assess The State-of-Health of Valve Regulated Lead Acid Batteries": Part III: Analytical Techniques. Proceedings of the 1994 INTELEC Conference, Vancouver BC.: pp 282-291.

4. M. J. Hlavac; "VRLA Battery Monitoring Using Conductance Technology": Part IV: On-line State-of-Health Monitoring and Thermal Runaway Detection/Prevention. Proceedings of the 1995 INTELEC Conference, The Hague, The Netherlands: pp 284-291.

5. D. O. Feder; "Performance Measurement and Reliability of VRLA Batteries" Proceedings of the 1995 INTELEC Conference, The Hague, The Netherlands: pp 22-28.

6. J. Poulin; R. Heron; D. Mailloux; "An Expert Management System for VRLA batteries in Remote Telecommunications Centers" Proceedings of the 1994 INTELEC Conference, Vancouver BC.: pp 497-504.

7: T. Taylor "Generic Requirements for the Detection and Control of Thermal Runaway in VRLA Batteries" Bellcore Document GR-1515-CORE, Issue October 1994.

Appendix A - Rev. 1.1 Corrected Data Points

String 1

Cell #	Float Voltage	Cond. KMhos	% Cap.
1	2.23	2.44	53.9
2	2.23	2.09	15.4
3	2.23	2.18	24.3
4	2.22	2.14	15.4
5	2.22	2.44	40.6
6	2.23	2.52	41.0
7	2.23	1.98	3.2
8	2.23	2.65	68.4
9	2.23	1.85	0.8
10	2.23	2.29	32.9
11	2.23	2.27	27.0
12	2.24	2.09	21.5
13	2.24	1.86	7.6
14	2.23	2.39	53.9
15	2.23	2.24	32.5
16	2.22	2.39	76.6
17	2.22	1.99	6.1
18	2.23	2.50	72.6
19	2.23	2.83	68.5
20	2.22	2.92	68.4
21	2.22	2.67	61.7
22	2.22	2.20	23.7
23	2.22	2.04	8.6
24	2.23	2.42	51.8

String 2

Cell #	Float Voltage	Cond. KMhos	% Cap.
1	2.23	2.13	9.9
2	2.23	2.39	30.8
3	2.22	2.43	25.7
4	2.35	2.01	0.1
5	2.23	2.45	36.2
6	2.22	2.48	42.0
7	2.23	2.53	49.2
8	2.22	2.18	0.5
9	2.23	1.02	0.0
10	2.23	1.83	1.0
11	2.22	1.95	1.0
12	2.22	2.39	34.8
13	2.22	1.99	0.1
14	2.23	2.07	0.9
15	2.22	2.13	8.2
16	2.24	3.40	100.0
17	2.23	2.61	41.3
18	2.24	2.88	77.4
19	2.22	2.14	9.9
20	2.23	2.67	58.8
21	2.23	2.04	0.1
22	2.24	2.50	30.0
23	2.23	2.43	28.5
24	2.24	2.77	53.6

String 3

Cell #	Float Voltage	Cond. KMhos	% Cap.
1	2.25	2.83	87.2
2	2.25	2.09	15.4
3	2.24	2.56	69.6
4	2.24	2.15	44.1
5	2.25	2.34	44.8
6	2.25	2.03	25.5
7	2.26	2.29	28.3
8	2.25	1.57	0.3
9	2.25	1.80	0.8
10	2.24	2.17	35.2
11	2.28	1.13	0.1
12	2.25	1.98	13.9
13	2.26	1.88	3.0
14	2.25	2.52	71.3
15	2.26	2.02	25.1
16	2.25	1.64	0.3
17	2.26	2.02	9.5
18	2.25	1.78	1.0
19	2.25	2.10	14.5
20	2.25	1.86	1.3
21	2.26	2.31	40.0
22	2.26	2.30	42.9
23	2.26	2.25	47.0
24	2.26	2.46	65.7

String 4

Cell #	Float Voltage	Cond. KMhos	% Cap.
1	2.26	2.01	29.9
2	2.26	2.41	64.5
3	2.26	1.87	5.1
4	2.26	2.05	32.2
5	2.25	2.10	14.6
6	2.26	2.34	59.2
7	2.25	2.64	70.5
8	2.25	2.86	74.3
9	2.26	2.80	68.7
10	2.25	2.90	77.8
11	2.25	2.70	93.5
12	2.26	2.87	88.0
13	2.24	3.09	78.9
14	2.26	2.84	84.6
15	2.25	2.86	99.5
16	2.24	3.16	98.5
17	2.25	2.79	80.2
18	2.26	2.39	43.8
19	2.26	1.75	0.8
20	2.25	2.48	64.4
21	2.25	2.26	34.0
22	2.27	1.89	3.5
23	2.26	1.99	25.7
24	2.27	1.97	22.8

String 5

Cell #	Float Voltage	Cond. KMhos	% Cap.
1	2.25	3.08	94.4
2	2.27	3.49	114.2
3	2.25	2.63	73.6
4	2.27	2.30	32.5
5	2.25	2.87	76.8
6	2.26	2.59	72.3
7	2.24	2.17	31.6
8	2.24	2.59	54.0
9	2.25	2.94	87.9
10	2.27	2.42	52.1
11	2.26	2.56	70.2
12	2.27	2.54	73.2
13	2.26	2.79	91.1
14	2.26	2.51	66.8
15	2.26	2.56	55.6
16	2.26	2.30	39.7
17	2.25	2.54	59.6
18	2.26	2.52	43.6
19	2.26	2.33	63.3
20	2.26	2.34	63.6
21	2.25	2.85	85.1
22	2.26	2.28	36.6
23	2.24	2.37	52.2
24	2.26	3.18	108.4

String 5 Reconfigured

Cell #	Float Voltage	Cond. KMhos	% Cap.
1	2.25	3.08	94.4
2	2.27	3.49	114.2
3	2.25	2.63	73.6
5	2.25	2.87	76.8
6	2.26	2.59	72.3
9	2.25	2.94	87.9
11	2.26	2.56	70.2
12	2.27	2.54	73.2
13	2.26	2.79	91.1
14	2.26	2.51	66.8
21	2.25	2.85	85.1
24	2.26	3.18	108.4
4	2.27	2.30	32.5
7	2.24	2.17	31.6
8	2.24	2.59	54.0
10	2.27	2.42	52.1
15	2.26	2.56	55.6
16	2.26	2.30	39.7
17	2.25	2.54	59.6
18	2.26	2.52	43.6
19	2.26	2.33	63.3
20	2.26	2.34	63.6
22	2.26	2.28	36.6
23	2.24	2.37	52.2