# Intelligent Monitoring System Satisfies Customer Needs for Continuous Monitoring and Assurance on VRLA Batteries

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Abstract - Telecom standby power systems being installed or modernized today primarily use VRLA batteries. Many customers ask for diagnostic and monitoring tools, and some sophisticated users want battery monitoring and diagnostic *systems* that also predict 1) available support time during an ongoing discharge, and 2) remaining battery life prior to replacement. GNB has found only one monitoring system that is comprehensive in monitoring, analyzing and predicting battery data. The "Intelligent Monitoring System", or IMS, is a low-cost universal battery and power monitoring system suitable for implementation across the network. IMS monitors and reports on actual events, which the power system owner wishes to know about, or other events that (from a battery technology point of view) may affect the condition of the installation. Such real-time expert-based systems, which utilize the knowledge of many parameters in data analysis, have the best prospect of satisfying the demands of the more sophisticated VRLA customers for diagnostic and predictive capability.

## I. INTRODUCTION

Battery reliability in standby power systems has become more acute in modern communication networks because of their increased use for data transmission and multimedia content than just voice. As computers and communications converge, as cable television and utility power companies enter telephony, and as remote, unmanned sites in the distributed wireless network architecture continue to proliferate, many more companies besides traditional telecom operators are depending on standby power systems to perform when needed. All these companies have limited knowledge and experience with batteries and need assurance that the batteries in their power plants will perform when needed.

Telecom standby power systems being installed or modernized today primarily use VRLA batteries. The rapid absorption of VRLA batteries, and their use in applications where flooded batteries would not or could not be used, has been accompanied by reports of VRLA batteries not meeting customer expectations in the areas of reliability and service life. Over the last 15 years, engineers from GNB, one of the major suppliers of VRLA batteries in the world, have reported[1-4] on several design and process advancements to improve VRLA

battery reliability and address customers' changing needs. Many customers have asked for diagnostic and monitoring *tools* that will trigger alarms so that appropriate action can be taken before the standby power system fails to perform when needed. The more sophisticated users want battery monitoring and diagnostic *systems* that also predict 1) available support time during an ongoing discharge, and 2) remaining battery life prior to replacement.

## II. DIAGNOSTIC TOOLS

GNB engineers have studied the diagnostic tools available to the user over the last few years. Several instrument manufacturers have promoted measurement of impedance/resistance or conductance as a diagnostic tool. The results of GNB's study covering data collected using impedance meters from Elcorp and Alber and a conductance meter from Midtronics were reported recently [5]. It has been found that 1) impedance and conductance readings on new GNB Absolyte IIP VRLA cells ranging in capacity from 100 to 1600 Ah have a 10 to 20% variation, even under ideal measurement conditions, 2) readings on cells being discharged showed that increases in cell impedance greater than the normal variation can be detected only when the depth-of-discharge is greater than 70%, and 3) field measurements can only be used to identify cells with gross problems because such readings are not sufficiently discriminative for inferring available capacity. This is especially true for impedance and conductance readings taken sporadically as "snapshots."

Recent claims that cell conductance and impedance readings alone are the definitive means to determine battery "state of health" have not been supported by convincing data. Indeed, to date there is little published data of the long-term trends of cell impedance or conductance for telecommunications batteries. This is related to the fact that on-line measurement of individual cell conductance or impedance *is not a trivial* technical challenge, particularly for larger capacity VRLA cells. Most of the popular impedance and conductance meters *are incapable* of automatically trending the in-situ, on–line impedance of individual cells and cell interconnections in the range of different power installations often encountered in telecommunications applications.

Figure 1 shows the long-term trends of the average impedance of very large capacity (> 3000 Ah) 2V VRLA AGM cells installed in 3 parallel 48V banks in standby service in a controlled environment (at 25°C). This is believed to be the first published logged trend data of single cell impedance over such a time period. The data was collected on-line and includes the noise induced by the telecom system backed up. The battery had multi-parallel intercell connectors and had very low impedance. These results show that it is possible to consistently measure very low impedance values (*ca* 70 micro-ohm) in an active (on-line) environment.

*Figure 1: Long term trend in cell impedances (3-hour averages) of 2V AGM VRLA cells in a battery of very large (>3000 Ah) capacity comprising three (3) parallel banks of 48 V each.*
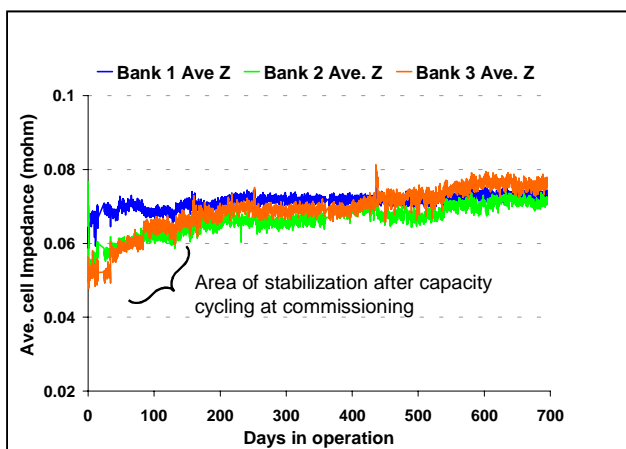


Of particular interest from a battery technology point of view is the real and unilateral trend towards higher impedances over time. The average cell impedance increased 14%, 30% and 49% for Banks 1, 2 and 3, respectively, over the average impedance value after the 100-day stabilization period. It is pointed out that the battery is very healthy and each bank delivered its full rated capacity; indeed there has been a slight increase in measured capacity. While the increase in impedance is measurable, the change is not yet sufficient to be reflected as a decrease in cell capacity. In the range of such low measurements, variations in the reading can range up to 25% of the mean. Therefore, snapshot impedance data collected by the use of impedance or conductance meters has very limited utility, particularly in the case of large battery installations with cell impedances under 100 micro-ohm.

Furthermore, we contend that trending of resistance (or impedance or conductance) data is only one useful factor in predicting battery state-of-health, and assert that this data set is not sufficient by itself to be an accurate predictor of state of health or battery capacity.

Continuous monitoring of several parameters and a rigorous analysis of the data are required to determine battery state of health and verify and validate the reliability of VRLA batteries. IEEE and IEC guidelines also recommend trending of impedance/conductance measurements along with others as an aid in the diagnosis of battery state-of-health. The case for continuous monitoring has been made before and several techniques have been proposed, particularly for the UPS application. GNB conducted a study of a broad spectrum of commercially available battery monitors. These units vary based upon 1) the number and type of physical parameters measured, 2) the usefulness of output from the monitoring system, and 3) the interface capabilities for use by the user/customer. We describe below what a comprehensive monitoring system should be able to do.

## III. CONTINUOUS MONITORING: PHYSICAL PARAMETERS

The physical parameters to be monitored are voltage, temperature, current and impedance or conductance.

### A. VOLTAGE

**Bus Voltage** – It is critical that the charger is set to the proper voltage for the prevailing ambient temperature to avoid problems associated with undercharging or overcharging. Unfortunately, simply assuring that the charger voltage is set correctly in no way guarantees that each replaceable unit in the battery is charging at the proper voltage.

**String Voltages** - If there are parallel strings connected to a charger, then each string voltage will float at the set voltage but the float current in each string will vary depending on the ohmic resistance in the connection to the bus.

**Mid Point Voltage** – Some battery monitors measure the mid point voltage of each battery string. This is a very simple approach to help detect voltage deviations within the string. The monitor will alarm when there is a sufficient imbalance in the half-string voltage caused by one or more blocks (or cells) that have deviated from the pack on voltage. Mid point monitoring has significant limitations. As the system voltage increases, mid-point voltage monitoring loses resolution and the ability to discern a deviant cell. Resolution is also lost as the manufacturer's float voltage range increases. The lower the resolution, the lower the likelihood that the monitor will detect a deviated cell voltage.

**Individual Cell or Block Voltages** – To achieve the maximum benefit of voltage monitoring, the user should measure the voltage of every replaceable cell or mono-block. The user will be notified immediately when any condition causes a single cell to deviate from specification. The key benefit to the user is that remedial action can be initiated before the deviated cell can cause prolonged under- or overcharging of some of the remaining cells.

Even measuring every cell voltage is not good enough to diagnose all potential problems with a battery. Therefore, many battery monitors today measure other physical parameters.

## B.    TEMPERATURE

Chemical reactions internal to the battery are driven either by voltage or temperature.   The hotter the battery, the faster chemical reactions will occur.  Grid corrosion and gassing are the two most common adverse chemical reactions associated with battery life.  For the user to have any chance of understanding battery life, the temperature of the battery must be measured and monitored.  Also, temperature measurements greatly aid in the detection of the onset of thermal runaway.   The best monitoring systems provide both an ambient temperature as well as various temperature measurements on the battery itself. Alarm conditions  arise when 1) the ambient is out of specification, 2) the battery is too hot relative to ambient, and 3) there is a temperature imbalance within the battery. It is important to note that simple, linear averaging techniques do not accurately account for temperature effects on battery life.  Given the Arrhenius relationship (i.e. doubling  of reaction rate every 10 $^o$C), the time at any temperature should be properly weighted to determine equivalent life at 25 $^o$C.  Thus, an hour at 35 $^o$C is equivalent in battery life to two hours at 25 $^o$C.

## C.    CURRENT

There is usually a dramatic difference in the discharge current and the float current of a battery.  As an example, a battery with a rated (8 hour rate to 1.75 VPC) capacity of 800 Ah may be discharged at 100 A.  But when it is fully charged, it can accept up to 400 mA on float at 25 $^o$C.  It is very difficult and expensive to measure current over such a broad range.  Therefore, monitoring systems elect to ignore this physical input.  But there is value to understanding current to detect the state of the battery (i.e. discharge vs. charge vs. float) and the onset of thermal runaway.  There is also great value in understanding the cumulative amount of energy either delivered or received during these various states in understanding and predicting remaining battery life.  Thus, it is essential that the current is monitored on charge as well as discharge.  If the battery comprises parallel  strings then each string current should be monitored.

Accurate measurement of the relatively small float current, the recharge current and the relatively large discharge current is crucial to achieving the reasonable accuracy in the prediction of remaining run time or life. Proper attention is required to the selection of the current measuring devices.

## D.    IMPEDANCE / CONDUCTANCE

As discussed, inferences from snapshot impedance and conductance readings are subject to considerable (up to 25%) variation.  But impedance or conductance trended over time can be _a_ reliable source of information regarding a battery's health [6].  As with voltage, the smaller the measurement blocks, the greater is the value of the data.   Therefore, a unit capable of single cell impedance measurement offers the greatest value to the user.

Cell impedance varies most with the concentration of the electrolyte, temperature, and the conductivity of the current carriers.  A deterioration in battery state of health is typically associated with the loss of conductivity of the current carriers (i.e. grids, active materials, straps, etc.). But to accurately assess health from impedance readings taken at different times in a battery's life, the readings must be compensated for changes in temperature and electrolyte concentration.   Impedance of the intercell connectors in a battery can also be monitored and can provide useful information about battery condition.

# IV.    CONTINUOUS MONITORING: USEFULNESS OF OUTPUT

The utility value of the monitoring system will increase with a) the number of physical parameters measured, b) the ability to link multiple physical parameters for alarming, c) the ability of the monitoring system to predict run time during discharge, and d) the ability of the monitoring system to predict the state of battery health.

## A.    NUMBER OF PARAMETERS

The cost and complexity of battery monitors typically increase with the number of physical parameters measured.  But as noted in the previous section, each physical parameter measured adds to the accuracy and diagnostic capability of the monitoring system.

Table 1. Capability of Monitoring Systems and measured parameters

| Physical Parameter | Shorts | Thermal Runaway | Predict Runtime Lookup | Predict Runtime Universal | State of Health |
|---|---|---|---|---|---|
| Cell V | X | X | X | X | X |
| Temp. | | X | X | X | X |
| Current | | | X | X | X |
| Impedance | | | | X | X |

## B.    LINKING PHYSICAL INPUTS

Many monitoring systems use a single physical input to trigger alarms.  However, to be meaningful, alarms have to be a combination of various conditions.  For example,

|   |   |
|---|---|
| IF | the battery is floating |
| OR | the battery is in equalize |
| AND | the ambient temperature is 25 $^o$C |
| AND | the battery temperature is >35 $^o$C |
| AND | the float current is greater than 500 mA |
| THEN | Alarm for thermal runaway |

The diagnostic usefulness of the alarms increases with the number of allowable conditional links. Many meaningful alarm scenarios can take up to eight conditional links for proper diagnosis.

## C.    REMAINING RUN-TIME PREDICTION

Many users want the monitoring system to provide an estimate of remaining run-time during a discharge. This allows the users time to dispatch generators to the site, or shed unnecessary loads from the battery. Several monitoring systems today provide run-time estimates based on look up tables or curvilinear fits. Typically, these compare the battery voltage under various loads and temperatures to factory stored data or constants in order to make the prediction for remaining run-time. Many of these monitors have demonstrated very good time-to-empty predictive accuracy. Unfortunately, extensive testing is typically required to characterize individual battery types. Managing the characterization process that defines the factory stored coefficients or data points is quite cumbersome. In addition, it is very inconvenient for telecom operators who have substantial existing battery assets that have not been characterized or those who use batteries from several suppliers. And above all, these methods do not always account for the age-related changes in cell characteristics.

An alternative to look up tables or curve fit prediction is the use of a combination of impedance and voltage measurements during discharge to predict remaining battery run time. The impedance of a battery increases during a discharge and during most of the discharge, the largest contribution is from the change in electrolyte concentration. During the initial periods of discharge the electrolyte resistivity decreases and compensates for most of the other contributors to increased cell impedance. This explains why the impedance behavior in a 450 Ah (C/8 rating) cell is not too different (within the 25% variation in readings) during the C/8 and C/24 discharges (impedance is independent of discharge rate for rates slower than say C/8) until 400 Ah have been removed (see Figure 2).

*Figure 2: Average Cell Impedance and Voltage during discharge at two rates on a 6-cell, 450Ah battery*
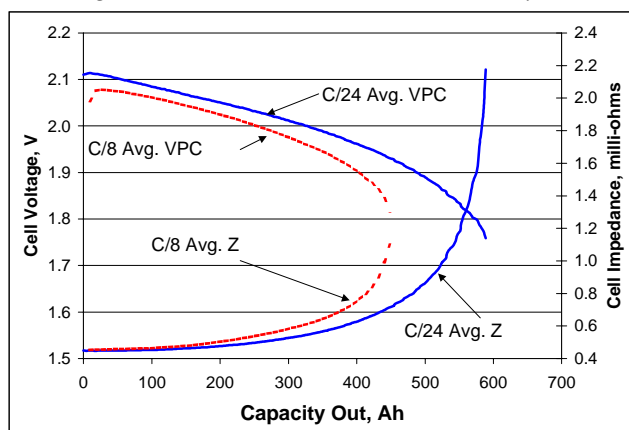


Beyond that point, cell impedance has a significant contribution from the changes in active material as well. The voltage profile during discharge is almost a mirror image of the cell impedance behavior but is sensitive to the rate of discharge. Therefore, by trending both the impedance and voltage of individual cells during discharge, a prediction can be made as to the remaining run-time at a given rate of discharge. While this technique is not necessarily as accurate as characterization approaches, it is perfectly useful for most users who are really interested in a time-to-run estimate for operational purposes rather than an exact capacity of the battery.

## D.    STATE OF HEALTH PREDICTION

Ultimately, a customer is most interested in whether the battery is capable of providing adequate back-up during a future power outage. An accurate state of battery health prediction can notify the user when a battery is not capable of delivering the requisite capacity (Ah) or energy (Wh), and also helps the user plan for an orderly battery replacement. It is important to stress that for long-life standby batteries on float duty in telecommunications applications, there is no *single* measurable parameter or battery characteristic that represents a direct state of health measure. Simply measuring cell voltages on float or float current over time is in itself insufficient to base an assessment of the "health" of the cells. The health of the stand-by battery systems is a matrix of multiple parameters, and excluding obvious catastrophic indicators, the state of health assessment must be a knowledgeable balance of multiple trends.

Individual Cell or Mono-block Spread: The individual building blocks must operate in concert to achieve the desired service life from the battery. Defective cells or blocks will put undue burden on the remaining good units. Therefore, a vital aspect of battery state of health relates to cell voltage uniformity within each parallel string. Most VRLA batteries will exhibit a convergence of individual float voltage within months of service or after a power outage. But as cells begin to fail, they may begin to diverge away from the pack. Therefore the spread in float voltage over time is a good indication of health.

Discharge Voltage Spread: Weak cells or mono-blocks within a series string will have lower voltages under load versus the battery string. This is an excellent means to pick out individual units that will impair the battery's ability to provide desired back up, and eventually, affect the health of the entire string.

Cell Impedance Spread: As stated earlier, healthy cells may exhibit a +/- 25 % variation in impedance. But this spread should not significantly increase as the battery ages. Therefore, if the spread in individual cell impedance does increase with time, this is likely an indication of a problem. Figure 3 shows the trended behavior of daily-averaged single cell impedance of 2V 500 Ah AGM VRLA cells in a 48V shallow-cycling photovoltaic power

system operating a remote area optical-fiber regenerator. The data was collected remotely over a period of nearly 500 days. Cell 20 is clearly "outside" the pack when the behavior of the cell is compared to the average, maximum average cell impedance (excluding cell 20) and the minimum average cell impedance. While the seasonal variation of cell impedances is evident, there is a clear increasing trend in the impedance behavior of Cell 20. Thus, a monitoring system can be used to identify a cell with a trend significantly different from the other cells in the bank.

*Figure 3: Impedance trends in a PV application*
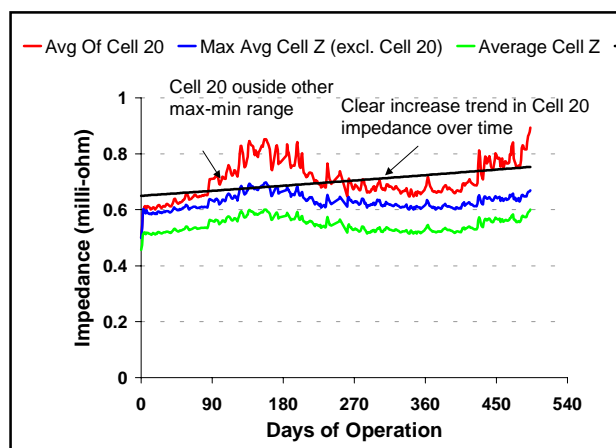


Corrosion Life – Float Applications: Most VRLA battery manufacturers design their lead-acid batteries such that at end of life the positive grid is corroded (the lead in the positive grid is slowly converted to $PbO_2$) beyond usefulness. In cells on float, the small current results in charging (offsetting self-discharge), gassing and recombination, and grid corrosion. Laboratory testing has demonstrated that the portion of float current associated with grid corrosion remains relatively constant within a useful range. Therefore, by keeping track of the cumulative amount of overcharge received by a battery, the user should have a fair estimate of the degree of positive grid corrosion.

Cycle Life: In telecommunication applications in emerging countries, standby batteries are discharged up to twice a day and so cycle life is very important in such locations. The active materials in a lead-acid battery have a finite capacity for cumulative storage and delivery of chemical energy. Over time, the morphology of the active materials in the plate changes, and the capacity of the cell decreases. Cells designed with robust active masses may fail due to a combination of grid corrosion and loss of active material surface area. Figure 4 depicts cycle life as a function of the amount of available energy removed for each cycle (depth of discharge) and the cumulative capacity delivered as a multiple of rated capacity. In the relevant range of 20 to 80 % DOD, the cumulative capacity delivered is about 1000 times the rated capacity. Therefore, a record of the cumulative capacity delivered by a battery over its life together with

the depths of discharge is valuable in predicting remaining life.

Impedance Trending: The value of impedance trending has been discussed with reference to Figure 1. It is important again to note that the largest contribution to cell impedance comes from electrolyte resistivity which is a function of its concentration [7]. Therefore to discern the degradation of the battery, it is important to have an accurate and repeatable measurement to catch these subtle impedance shifts. Laboratory testing to date has shown that many of the common failure modes in VRLA batteries are characterized by substantial (>50%) increases in cell impedance. Separator decompression is such a failure mode and has a large unfavorable effect on cell impedance and delivered capacity. It has been reported[4] that the addition of a small amount of water to the cells reverses the effect of separator decompression.

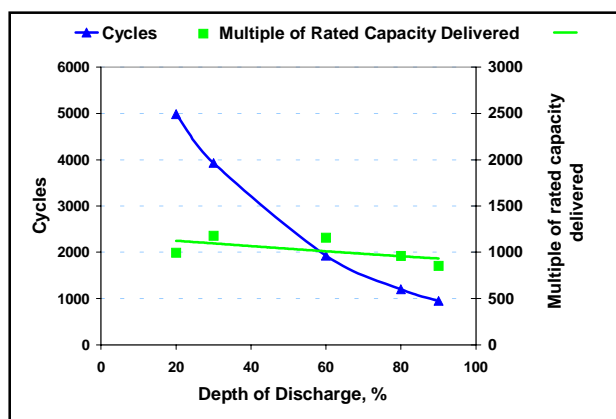*Figure 4: Cycle life and cumulative capacity delivered*



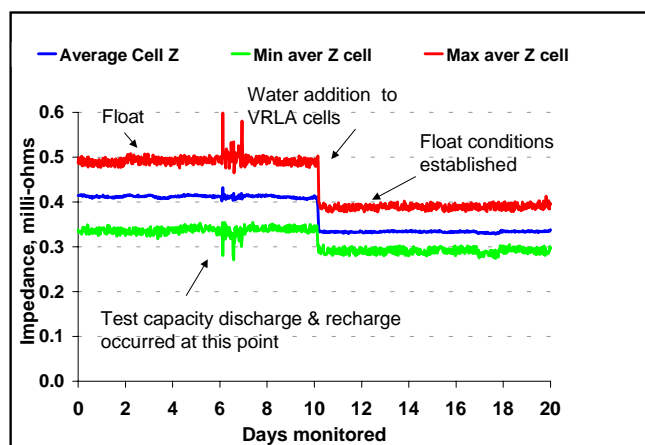*Figure 5: Impedance trends in a battery after reversing separator decompression*



Figures 5 shows the interesting behavior of 1000 Ah 2V AGM VRLA cells operating in a controlled environment on float in a 48V on-line system during the period where water was added to the cells in an effort to reverse separator decompression and reconstitute rated capacity.

As can be seen, the impedance of the cells prior to water addition is relatively high (correlated with low capacity). Even after discharges to correct the low capacity, the impedance remains virtually unchanged. On addition of the water, the impedance significantly decreases for all cells, and this is accompanied by a measured increase in capacity, almost equal to the rating. Over the subsequent monitored period, all cells exhibit a small, yet discernible increase in impedance on float. A small reduction in the recovered capacity was measured during a subsequent discharge test (after 35 days on float).

Additional failure modes are currently under study to assess their significance, and to determine if they can be characterized by a discernible increase in cell impedance. These include premature capacity loss (PCL, usually associated with antimony-free positive grid alloys) and negative plate depolarization.

## V. CONTINUOUS MONITORING: CUSTOMER REQUIREMENTS SATISFIED BY INTELLIGENT MONITORING SYSTEM (IMS)

User needs will vary greatly regarding what and how information about the battery is communicated. In a traditional central office, there is usually a service technician nearby that can immediately respond to a local alarm. Typically the batteries are flooded, so there are more diagnostic checks available to the technician (i.e. specific gravity and visual inspection of the cells). Finally, in a central office, the technician usually has a fair degree of training regarding battery service and safety.

At the other end of the spectrum are users with distributed powering. Typically the sites are remote, the batteries are of VRLA type, the maintenance is minimal, and the technicians have less battery diagnostic expertise. These users will require the monitoring system to communicate remotely as well as provide diagnostic assistance for the technicians.

Battery diagnostics required by the customer include state of health prediction, run time prediction during power outages, alarm, and troubleshooting information. In addition, the customer requires that battery monitoring systems be integrated into existing network communication and control systems, directly or by remote communications, through discrete contacts, text alarms, and serial protocol.

Commercial monitoring devices that merely log data and utilize a separate computer or similar platform to analyze the data at a later time ("batch process") are available. Many of these are surveillance systems only and do not satisfy the customers' needs for diagnostic and predictive

capabilities. Some of these shift the burden of data analysis to the user while some others conduct limited analysis of the collected data. But such analysis is not always based on the manufacturers' (or users') knowledge of battery performance and life; nor is it based on the relationship of measured parameters to battery behavior.

GNB has found only one monitoring system that is comprehensive in monitoring, analyzing and predicting battery data and can satisfy the customers' needs for diagnostic and predictive capabilities. In 1995, *Hawkins et. al.*[8] "examined user based rationale for the functionality of a battery or power monitoring system in telecommunications environment." They presented the "Intelligent Monitoring System", or IMS, a low-cost universal battery and power monitoring system suitable for implementation across the network on new and old, flooded and VRLA, monoblock or 2V batteries, as well as for power systems. The trended data on cell impedance and voltages shown in figures 1-3 and 5 earlier were collected online using IMS. This demonstrates the capabilities of IMS.

The purpose of deploying intelligent monitoring devices in telecommunications applications is to allow local determination of aspects about unattended events. One meaningful way to do this (in a way which does not require associated deployment of a new platform to support the power system monitoring itself) is to have a local expert system continuously assessing and interpreting the condition of the standby batteries and their operating environment.

IMS monitors and reports on actual events, which the power system owner wishes to know about, or other events that (from a battery technology point of view) may affect the condition of the installation. Event reporting is made possible by IMS's capability to capture unattended events at the individual cell level. For instance, IMS can capture and report on the individual cell performance during an unattended outage. When a battery fails to support the load in an outage, often there is follow-up work to determine the cause of failure. For battery systems that support the load for the duration of the outage, typically there is no interest about the performance of the cells. However, for aged batteries in service, it is not unusual that one or two cells may fail, yet the entire battery bank supports the load. The nature of those individual cell failures may represent an undetected risk to the installation (*i.e.* shorted cells, thermal runaway candidates on recharge, etc.). An intelligent monitoring system, with a local embedded expert system to interpret all the information that can be gathered during a discharge, can provide 1) a record of the outage, and hence automatically measure the system capacity, 2) identification of individual failed cells or monoblocks, and 3) notification to the network owners that a failed battery component was detected. Thus, IMS can provide a means to reduce the future possibility that the failed monoblock or cell might have caused a catastrophic failure to both the

installation, such as thermal runaway, and to the network operation, such as the inability to sustain the next outage.

## VI. CONCLUSIONS

The increasing use of VRLA batteries in modern telecommunication networks has given rise to increasing requests from the more sophisticated users for a battery monitoring and diagnostic system that can predict run time during a power outage, determine the state of health of the battery and report alarms that require corrective action to protect network integrity. The desired predictive capability is only possible through the monitoring of several physical parameters, the linking of these parameters for alarms, and a knowledge-based analysis of the multiple trends among the measured physical parameters. GNB has identified an Intelligent Monitoring System (IMS) that is capable of continuously measuring and recording all of the required physical parameters and then analyzing the data to satisfy the needs of the more sophisticated users. Furthermore, IMS is capable of being integrated into the users' network control system directly or remotely for it uniquely addresses the User perspective and requirements.

## ACKNOWLEDGMENTS

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