RELIABLE BATTERY SYSTEMS WON'T HAPPEN

WITHOUT PROACTIVE TESTING AND MAINTENANCE

What is required to guarantee a reliable system?

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INTRODUCTION

Our world today has become reliant on systems in support of a global economy and communication network that are powered by a combination of both DC and AC electrical power sources. These systems by their very nature must supply uninterrupted continuous power. The design of an uninterrupted power source must consist of a primary energy source, such as the national power grid, and a backup energy source that can power the load during any interruptions in the primary source. The backup or standby energy source for most critical applications consists of the following:

A. A temporary energy source that can instantaneously assume and support the load during momentary and short duration interruptions (fractions of a second to a few hours). Examples of such energy sources employed in today's designs are batteries and large flywheels.

B. A longer-term source that can support the critical load for hours or days until the primary source is restored. Examples include the diesel engine generator and large stationary battery banks.

There are a number of other technologies under consideration today and some are actually being employed in a few mission critical systems however the refinement of such technologies and their wide spread use has yet to be realized. The lead-acid battery is still the main energy source in use today and will be for the foreseeable future. Issues discussed in this paper will be limited to the lead-acid technology.

The main reason other technologies are receiving so much attention today is that many battery backed-up systems have not met the high reliability demanded by most customers. The keyword here is "many," because there are numerous battery systems working reliably.

Why are not all battery applications considered reliable? It is very simple; most battery customers do not understand batteries and, therefore, do not perform the necessary maintenance and test routines to assure themselves a reliable system.

The following sections will discuss why batteries fail and how these failures cannot only be detected early on, but how most of them can also be prevented.

BATTERY BASICS

To understand why all batteries eventually fail, it is necessary to know the basic construction of the battery and understand the factors that influence battery life and reliability. The following is a very basic explanation, and the author hopes that the electrochemists of the world will forgive some of the oversimplifications made.

The original, basic lead acid battery (called Planté after its inventor) is made up of pure lead plates that are placed in an electrolyte solution of diluted sulfuric acid. If an external voltage source is connected with the polarity shown, a current will flow through the battery, and the outer surfaces of the plates begin to transform as shown. The positive plate develops a very fine outer layer of lead dioxide (PbO_2), and the negative plate develops a layer of something referred to as sponge lead (Pb). See Figure 1.

Figure 1. Basic Lead Acid Cell

The conversion of the plates combined with the electrolyte (H_2SO_4) represents stored chemical energy that can be converted and delivered as an electric current through an external load when connected across the positive and negative terminals. The amount of material in the plates that converts is referred to as the active material, and the energy that can be stored is directly proportional to the amount of active material available.

The chemical formula simply shows the chemical changes that occur during charging and discharging. Fully charged, the battery is represented as $PbO_2 + Pb + H_2SO_4$, which means a positive PbO_2 plate plus a negative Pb plate and dilute sulfuric acid H_2SO_4. As the battery discharges, the active material on both plates converts to $PbSO_4$ (lead sulfate), and the electrolyte converts to almost pure water.

The original Planté design, still in use today, has the drawback that only a small amount of active material is available; therefore, this battery requires large plates and many of them in parallel to store sufficient energy for its applications.

The shortcoming in energy density of the Planté design led to the development of the pasted plate technology, which is the most popular plate design in use today. The pasted plate, shown in Figure 2, utilizes a lattice grid structure that is filled with active material.

Figure 2. Pasted Plate and Grid Structure

The active material, primarily made up of pure lead, is also referred to as "paste," since it is applied to the grid in the form of a paste. The paste, when applied, resembles wet concrete. The volume of paste applied in a fairly small space gives the pasted plate a great energy density advantage over the Planté plate.

The grid is a framework with a dual purpose. The first is to hold or support the active material, and the second is to carry current to and from the active material. Most grids are cast using lead alloys, due to their superior mechanical strength, although pure lead grids are available. Grids are most often rectangular in shape, with horizontal, vertical and possibly radial members, and a plate lug on the top edge. The plate lug will ultimately be joined, along with the lugs of other plates of the same polarity, to the cell post. Dimensions of the grid, as well as the number of members and their configuration, vary depending upon the application. For example, long, narrow, thick grids may be suitable for a cell designed for telecommunications applications; however, thin grids with an almost square shape may be more suitable for UPS applications.

As mentioned earlier, the capacity or amount of energy a battery can store is a function of available active material and acid available. The simplest way to increase a battery's capacity is to connect additional plates in parallel. Thus, the batteries produced today consist of an assembly of positive and negative plates insulated from each other by separators. The size of the plates obviously also impacts the capacity, and the battery manufacturers typically produce at least five different plate sizes.

TYPES OF LEAD ACID BATTERIES

The following two types of lead acid batteries are currently in use:

1. VLA (Vented Lead Acid) – This is the oldest and most reliable technology, characterized by an abundance of free electrolyte. All surface areas of the plates are submersed in the electrolyte. Water, in the form of hydrogen and oxygen gases generated during charging, is lost and must periodically be replaced.

2. VRLA (Valve Regulated Lead Acid) – The VRLA, sometimes referred to as sealed, has been evolving since the late 1970s and has become very popular, primarily because of the installed price. The VRLA is designed to theoretically not lose any water by recombining the hydrogen and oxygen gases given off during charging. VRLA cells have a small pressure controlled valve that keeps gases from leaving the cell unless the internal pressures exceed a set value. Another major difference with the flooded design is that the VRLA does not have any free-floating electrolyte; the electrolyte is suspended in either an absorbing glass mat (AGM) or a gel substance (GEL). See Figure 3.

A key point to remember is that the plates discussed earlier are essentially the same for both the flooded and VRLA design. The main design differences are how much electrolyte is stored and how it is stored.

Since the loss of water is an important maintenance consideration, lets look at how it happens:

· When a cell has reached full charge and cannot absorb any more energy, the charge current energy still flowing begins breaking down the water in the electrolyte into its two component gases (hydrogen and oxygen).

· In a VLA of flooded cell, the gases are free to leave the cell via a flame arresting vent cap, and it is therefore required that water be added periodically.

· In a VRLA cell, which was designed to eliminate periodic water additions, the gases recombine to form water again. The theoretical recombination efficiency is 99.9%. (In practice, VRLA cells do suffer from water losses, and this will be discussed in the next section.)

Figure 3. VRLA Battery

Note the white absorbing material between plates. It holds the electrolyte and provides electrical isolation between the adjacent positive and negative plates.

WHY BATTERIES FAIL

General

It should be noted that all lead acid batteries have a limited useful life. The normal failure mode that dictates the end of life of a well-maintained flooded battery is positive grid corrosion. As the grid corrodes, the effective cross section of the conduction path narrows, and the internal cell resistance starts to increase. At the same time, the grid structure starts to swell and deform to the point where the paste or active material loses contact with the grid structure. This problem also leads to increased internal cell resistance as the contact resistance between paste and grid increases. If the resistance increases are ignored, meaning that the battery is not taken out of service at the appropriate time, the positive grids will eventually lose their mechanical strength and start to break apart.

It is the author’s belief that due to the predictable decay of flooded cells, internal cell resistance measurements can be used to predict end of life. The normal life of a good quality flooded battery is twenty years.

VRLA product today only has about a seven to ten year life span, and these cells do not live long enough to die of normal positive grid corrosion. The most common cause for their early demise has been a drying out or loss of water in the electrolyte. There are also investigations being conducted that indicate that secondary reactions from internal recombination of hydrogen and oxygen gases may be adversely affecting the polarization voltage of the negative plates and/or accelerating positive grid corrosion. Both problems lead to a loss of capacity.

WHY BATTERIES FAIL PREMATURELY

The reasons that most batteries fail prematurely are related to one or more of the following:

1. Excessive cycling

2. Improper charging

3. Lack of temperature control

4. Installation

5. Manufacturing problems

6. Operational issues

Note that the user has control over most of the conditions that lead to premature failure.

Excessive Cycling

Every time a battery cycles (a discharge followed by a recharge), the electrochemical generator has to go to work, which involves converting acid and paste. As the paste on the positive grid changes from PbO_2 to $PbSO_4$, there is a large increase in volume, which puts pressure on the paste. The more the paste is expanded and then later contracted, the more the wear and tear on it. This means that deeper discharges are more harmful to the battery. Also, cycling a battery causes accelerated corrosion of the grid structure, which leads to shorter life. This is especially true for lead calcium batteries, which happens to be the most popular technology in use today.

The lead calcium battery's cycling capability depends on the depth of discharge. For example, it is only capable of 50 deep cycles (the removal of more than 80% of energy), but can deliver 300 cycles for a 25% depth of discharge cycle. A UPS battery which normally only delivers about 25% of its stored energy during its 15 minute rated reserve time can deliver 300 such cycles. If the load on the battery is less than 30 seconds (momentary power glitch), it can handle thousands of these short cycles.

Improper Charging

Battery manufacturers specify a voltage range for their various cells that must be adhered to. If the voltage on a given cell is allowed to go either higher or lower than the recommended value, it will have a detrimental effect on the life of the battery. It should also be noted that the specified voltage range is very temperature dependent. The right voltage for a battery at 77°F would be too high if the battery was operated in an ambient temperature of 90°F. It is important for a user to understand the interaction between voltage and temperature.

Low float voltage (Undercharging) – Undercharging causes sulfate crystals to form on the plate surfaces, since there is not enough current flowing to keep the battery fully charged. Sulfate crystals that harden over a long period of time will not go back in solution when proper voltage is applied and, therefore, result in a permanent loss of capacity. Extended undercharging will also cause a loss of active material from the negative plates.

High float voltage (Overcharging) – Overcharging causes excessive gassing of hydrogen and oxygen. This leads to loss of water in flooded cells and dryout in VRLA cells. High float voltage also causes higher float current, which in turn causes accelerated corrosion and shedding of active material from positive plates. The recombination of gases to form water in VRLA cells generates heat, and heat causes higher float currents. Therefore, excessive gassing in VRLA cells can lead to thermal runaway.

Lack of Temperature Control

Batteries are very temperature sensitive, and efforts should be made to maintain the operating temperature near 77°F. The proper temperature will optimize battery life and is especially critical for VRLA cells. The recombination of gases within a VRLA cell can only take place at a certain rate. If this rate is exceeded, gas pressure will build up beyond the safety valve level, and gases/water will be vented out and permanently lost. At 77°F, the highest float voltage at which a cell can still recombine all the gases driven off the plates is approximately 2.32 volts. If the cell temperature increased to 90°F while holding the voltage constant, the cell would dry out and possibly go into thermal runaway. Thermal runaway leads to a melting down of the jar and, under worst-case scenario, will lead to an explosion and fire.

It should be obvious from the above discussion that all VRLA applications should have tight temperature controls and/or temperature compensated chargers.

Low temperature – Battery capacity is diminished at low temperatures. For example, at 62°F, capacity is approximately 90% versus 100% at 77°F. At low temperatures, a higher float voltage is required to maintain full charge and, if the charger is not adjusted properly, cells may be undercharged, leading to the problems described under low voltage.

High temperature – High temperature causes loss of life. For every 15°F rise in operating temperature, the life is cut in half. High temperature causes increased float current, which means increased corrosion and, therefore, the loss of life. High temperature also causes gassing, which means loss of water in flooded cells and dryout and thermal runaway in VRLA cells.

Installation

A lot of battery problems stem from improper installations. A detailed discussion of these is beyond the scope of this paper, but some of the more common ones are the following:

Loose intercell connections – These can lead to abrupt failures, including fires.

Damaged post seals – Improper cell handling or not supporting cables can damage post seals. This allows acid to migrate up the post and corrode the post to intercell connection.

Not replacing shipping caps with vent caps – In flooded batteries, this creates internal gas pressures that will force gases to escape past the post seals, causing post corrosion.

Manufacturing Problems

Manufacturing problems actually represent a small number of the total. Some of the more common problems, which may not show up for years, are the following:

Faulty post seal design – A leaky post seal allows acid to migrate up to the post/intercell connection area, causing a connection problem. Sometimes a new design appears to work well, but then suddenly starts failing after six to eight years in the field.

Internal connection problems – Quality problems in the connection between grid tabs and the interconnecting bus have been reported from time to time. In multicell jars like six or twelve volt modules, the intercell connection between adjacent cells may fail as a result of a poor lead burn.

Paste – Problems in the paste formula or improper curing of the paste can have a major impact on the capacity the battery can store. Some new batteries have been delivered at less than 50% capacity.

Operational Problems

· Discharge without recharge – A fully discharged or near fully discharged cell will be damaged and possibly ruined if not recharged within 24 to 48 hours. As a battery discharges, the electrolyte starts changing from an acid solution to almost pure water when the battery is fully discharged. Lead dissolves in water, and some of the plate material mixes with water to form lead hydrate. Lead hydrate causes the plate surfaces to turn white and, because it is conductive, it forms a short circuit between the plates, rendering the battery irreversibly damaged.

· Over discharge – Over discharge causes abnormal expansion of the active material in the plates, which leads to permanent damage and also recharges problems. This can happen in lightly loaded UPS systems that experience an extended power outage.

· Excessive discharging (same as excessive cycling) – Some users have local requirements that call for testing their critical backup systems either weekly or monthly. If this testing includes cycling the battery, it will severely limit the life of the batteries.

Failure Analysis Summary

Battery system failure modes can be broken down into the following two major categories:

1. Abrupt failure – This is a sudden loss of the battery system without any warning while the system is trying to perform its intended mission. This is the worst-case scenario, as it will lead to very expensive failures. In a data center application, even a momentary loss may result in millions of dollars worth of damage. An abrupt failure is cause by an interruption in the conduction path. Typical failures are:

· Faulty intercell connection – This could be an installation problem or a severely corroded connection.

· Internal conductance path problems – Remember, the current has to flow through the post, to an internal bus, to the grids, through the paste and electrolyte, to the opposite polarity plate, and then back out through the other terminal post.

Abrupt failures can result from a totally corroded grid that is breaking apart and only able to pass a low current flow. It can also result from a terminal post that has lost its copper insert. High current batteries have a copper insert in their posts and, if this copper is exposed to acid through a small void in the lead coating, the copper will dissolve and leave only a small lead coating to carry the current. VRLA cells that have totally dried out can also be viewed as conductance path failures, since they have no effective path between adjacent plates.

2. Low capacity failure – This is a failure to support the load for the required period of time. Low capacity results from both mechanical conductance problems as well as electrochemical problems. As a battery ages and its conductance path (grid corrosion, paste to grid connection) starts to deteriorate, the internal resistance increases. When the battery is placed under load, the voltage drop across the internal resistance will cause the overall battery voltage to reach the end voltage before its rated time.

The VRLA battery has the additional problem that, as it loses water due to dryout, it loses capacity. In essence, it loses the energy storage required for a full capacity battery.

The capacity problem is a slowly developing problem that is easily detected and, most of the time, does not cause expensive outages, since it is rare that full capacity is required during an outage. Typically, an outage is a short momentary event, and an emergency generator is usually part of the backup scheme.

It should be obvious from the preceding discussion that almost all battery problems can be detected by an increase in a cell’s internal resistance, and close monitoring of this parameter can avoid disastrous failures.

Resistance measurements are mandatory for applications that cannot tolerate a loss of power. The only battery test that can provide better information on a system's state of health is a full capacity test, which is also recommended on a scheduled basis.

GUARANTEEING A RELIABLE BATTERY SYSTEM

Guaranteeing is a strong word, but the author firmly believes that a competent maintenance organization, using the right tools, can assure a safe and reliable system.

Early detection is key

Again, it must be reiterated that batteries will and do fail. The key to operating a reliable system is to detect problems at an early stage before these problems can cause a system failure.

How is early detection accomplished?

Monitoring all the important parameters on a continuous basis and performing proactive tests accomplish early detection.

Parameters such as voltage and temperature are primarily measured to provide an indication of the operating environment, so that optimized conditions can help extend battery life. Voltage measurements, except for detecting a cell with internal shorts, do not provide any clues to the battery's ability to support a load.

The only viable tests for detecting performance problems at an early stage are internal resistance tests and capacity tests. Both of these tests are recommended by IEEE standards and have been field proven for many years.

Resistance testing has become very popular and has been accepted by the industry as a strong supplement to capacity testing, and many leading battery manufacturers provide warranty settlements based on these readings. IEEE standards call for periodic capacity testing, but the typical test intervals are five years for flooded cells and yearly for VRLA. Most people do not feel comfortable not knowing their battery's health status in between capacity tests and supplement them with quarterly resistance tests. Other battery users who cannot take their system offline or find the funding for capacity testing rely solely on resistance measurements.

Specific Recommendations

IEEE Standard 450 (Flooded) and IEEE Standard 1188 (VRLA) provide recommended maintenance and test practices for large lead-acid storage batteries. These practices, which call for monthly, quarterly, and annual inspections, are designed to maintain a reliable battery system. They also call out the required actions to optimize battery life. Unfortunately, most battery users, except for the nuclear power industry, do not perform more than a fraction of the inspections and tests recommended.

The author, who strongly believes in the IEEE's recommendations, but also recognizes that economic and operational constraints exist in real life, hereby offers the following specific recommendations, which actually go well beyond the IEEE in scope:

1. Install a permanently mounted battery monitor system, capable of continuously making all of the voltage, current, temperature, and resistance measurements called for by the IEEE standards.

2. Respond to any out-of-tolerance conditions and take the corrective action recommended by the IEEE or battery manufacturers.

3. Trend monthly data from internal cell resistance measurements and take action as follows:

· If any resistance reading exceeds the baseline value for that model cell by 50% or more, then replace the cell without any further testing.

· If the resistance value is between 20 to 50% greater than baseline, then perform a capacity test to verify its state of health. If capacity is 80% or less, then replace the cell as soon as possible. If greater than 80%, then continue to watch for further increases in resistance. If capacity testing is not an economically viable option, then replace the cell. Keep in mind that capacity testing can be performed on the entire string offline or can be performed on a single suspect cell online.

4. Perform capacity testing in accordance with the IEEE recommendations. This should only require the rental of a load bank, since the monitor will log data during the discharge test. Of all the capacity tests recommended, the acceptance test performed right after installation is the most important one and must be performed. Why would anybody install a backup system without knowing whether it was going to perform or not?

5. Analyze data from the monitor at least once monthly, and perform an annual sanity check on the monitor itself to verify that it is properly calibrated and working correctly.

Monitor Justifications

· Increased reliability. The monitor is online continuously, 7x24 coverage versus maintenance visits once or twice a year, and will alarm immediately when something is wrong.

- A monitor will not only take a lot more readings than any maintenance team, but more importantly, it will take consistent readings that can be trended with a high degree of confidence.
- A monitor will detect and record any and all power outages. The data will show how well the battery performed during an actual outage. The record of how many discharge cycles and how long they lasted will help settle warranty claims.
- The data from a monitor will help predict end of life and will allow for a scheduled and orderly replacement.
- A monitor used as part of a scheduled load test program can identify weak or failed cells or Mono-Blocs (multi-cell units).
- Batteries can be monitored remotely with a full, real-time display of all parameters.
- Regularly scheduled maintenance visits can be reduced to once a year, creating on-going savings that pay for the initial cost of the monitor.
- Safety! A monitor eliminates the need for maintenance personnel coming in contact with the battery. This eliminates accidental harm to both the battery and the maintenance person.

Remote Monitoring

Too many people who install monitors believe that, somehow, all will be well with their battery. Unfortunately, the monitor only collects data and reports on out-of-tolerance conditions. Someone is still required to analyze the data and decide on corrective actions.

In order for monitoring to be completely effective, a central computer monitor site is required. The central monitor has two-way communication with all battery sites and receives all alarms. The alarms are logged and forwarded to the appropriate maintenance personnel via pager and/or fax. The central computer polls all remote sites at least once a week, primarily to verify the communication link and make sure the local monitors are functioning.

The central computer site must either be staffed by or supported by a battery expert who can identify problems and instruct maintenance personnel in the field. Analyzing data, especially the trending of internal cell resistance measurements (state of health checks), requires someone who is well trained in battery testing.

Who should do the monitoring? If the decision is made to use in-house resources, then it is imperative that the battery data be readily available to the resident battery expert. Some users that do not have the proper personnel or don’t know how to integrate the data with their present programs should consider an outside source. As long as the proper monitor is selected, outsourcing the monitoring of the battery monitors make a lot of sense. Contracting out the battery monitoring responsibility can range from simply reporting the problems and recommending corrective actions to the outside source's taking on the entire responsibility.

SUMMARY

- The pasted plate lead-calcium battery is the most popular battery in use today.
- There are two lead-acid designs in use today: the flooded and the valve regulated (VRLA).
- Of the two designs, the flooded battery is the more reliable and should be the battery of choice for mission critical applications. VRLA batteries have the advantage of lower cost and lower space requirements.
- Controlling the operating environment of a battery (charging and ambient temperature) will optimize the life of the battery.
- Almost all battery failure modes increase the internal cell resistance.
- Internal cell resistance is (except for a capacity test) the most reliable indicator of a battery’s state of health.
- The key to guaranteeing a reliable battery system is to be able to detect failures at an early stage.
- Using a permanently installed battery monitor is the only way to guarantee a reliable battery system.
- Remote maintenance using battery monitors is the wave of the future and is the only way to manage large numbers of battery sites cost effectively.
- The cost of battery monitoring can be justified by:

a) Increased system reliability (no costly downtime)

b) Personnel safety (no human contact with high voltages)

c) Reduced labor time (fewer visits)

- For a remote battery maintenance system to be effective, someone familiar with batteries must manage it.