AN INNOVATIVE DIGITAL FLOAT CURRENT MEASUREMENT TECHNIQUE – PART ONE

Arnold J. Brown
Product Line Manager

Pierre Richard
Research and Development Engineer

Multitel, Inc.
2905 rue de Celles
Quebec City (Quebec)
Canada G2C 1W7

Abstract

Several practical methods exist to detect potential failure modes in electrochemical batteries. Thermal runaway phenomenon is described often as a failure mode in Valve-Regulated Lead-Acid (VRLA) type battery cells. This paper will present an innovative and practical method of measuring Float Current. Float current is claimed to be capable of detecting thermal runaway as well as other predominant failure modes, at the root[1]. It is also claimed that Float Current can detect a large number of other non-hazardous VRLA battery problems before they can become a threat to the end-user's service quality[2]. Float Current may also be a key parameter in determining a battery's state of health and remaining life / capacity criteria.

This paper describes Float Current measurement and its related theoretical benefits. It explores different measurement techniques and presents a new innovative digital measurement method. Battery laboratory results will also be presented to define how Float Current measurement can detect various battery problems. A proactive detection of these battery problems will help users to eliminate service loss to the end user.

Introduction

Various electrochemical battery technologies are used as secondary storage in most standby backup power systems. The state of health of said battery subsystem heightens a monumental concern when the reliability of distributed telecommunication networks during a commercial power outage are at stake.

A battery backup failure becomes an accountable error when a service provider looses service. A loss of service becomes an automatic loss of revenue. Accountability also becomes an issue when the service provided to the end user has to be categorized as a lifeline. Finally, the end users perception of a service provider's reliability is put in jeopardy when any service is lost. This tarnished reputation can quickly become another costly problem that can not be taken lightly.

To further aggravate the severity of the previous mentioned concerns, there has been significant data published that focuses on the inability of a VRLA battery to fail gracefully[3]. With the incorporation of VRLA as the base technology for battery plants in the standby backup power market offering, the problem quickly grows.

The failure mode used by a battery manufacturer to determine a VRLA battery's service life is typically the same failure mode used to determine a vented lead-acid battery's service life. This natural aging failure mode is usually characterized by a loss of active material over time within the electrochemical process of the cell. A trend in published data however, points towards the presence of various other failure modes which determines a much shorter expected life with respect to a VRLA battery cell. Over-polarization of the positive plate, internal short circuiting of the plates dissolving into solution, plate sulfation, dryout, strap corrosion, and negative plate discharge are only a few of the additional failure modes that are not accounted for when a manufacturer determines a VRLA battery's rated life[4].

In the past it was adequate, when performing routine maintenance on vented lead-acid batteries, to record individual cell voltages, record individual cell specific gravity measurements and verify the electrolyte level. This mated with a routine visual check to insure positive post seals and to identify any interconnect and/or terminal corrosion provided, in the past, a reliable indication as to the state of health of the battery plant. If the battery plant's state of health was verified within the operating parameters, it was only a matter of checking the torque on the terminal cell interconnects and moving on. This practice was all that was necessary to provide a high level of confidence that the battery plant would sustain the operator's revenue-producing equipment in the event of a power failure.

As of late, there is an increased trend towards distributed telecommunication networks[5]. Some examples of such are Controlled Environment Vaults, Telecommunication Equipment Huts, Optical Network Units, etc. Designers and integrators are finding clever functional areas to place the standby battery plants. However, these areas have been typically difficult to access for visual maintenance much less for any servicing. This coupled with the increased use of other cell technologies where the past indicators of battery health are no longer present; an identifiable risk of disaster becomes unmistakable. Some examples of cell technologies are redesigned vented lead-acid batteries; the previous mentioned VRLA cells and the Advanced Nickel Cadmium (ANC) cells[6], with their single point watering system. Add another factor with the above mentioned VRLA technology possibly failing via other failure modes[7] than how the life was rated or with a new cell technology and the uncertainty in its long term reliability, and the risk of catastrophic failure become tremendous. The confidence that the battery plant would sustain the service provider's revenue producing equipment in the event of a power failure is missing. Also, the possibility, especially in the case of a VRLA battery plant, of catastrophic disaster due to a battery failure mode like thermal runaway introduces an even greater risk.

Float current monitoring for battery management

Past research and published technical papers presented at various conferences have concluded that a battery's required float current, necessary to maintain a given charge, is a highly accurate and reliable indicator in determining the state of health of a battery. This is especially critical with the sealed VRLA battery where it is difficult to identify what is happening inside a cell before a scenario is already a catastrophe. It has also been touted, in published technical papers, that a battery's required float current becomes perceivably dynamic considerably prior to other easily measured parameters, such as temperature and voltage mid-point.

Until recently, a reliable and accurate method for measuring the float current was often intrusive and expensive. Many times, reading a float current meant opening a battery string and installing a complex and usually expensive instrument. It is not typically acceptable, to a service provider, to open a string and install equipment that is seen as a single point of failure within the standby backup power system. Also, a high increased cost attributed to the non-revenue producing aspect of a service provider's network is very difficult to justify no matter what the benefit.

Also, in the past, the equipment used to measure float current accurately was not capable of withstanding the discharge and recharge current associated with a commercial power failure and return. This meant that the apparatus could not be permanently installed at a service provider's site. Or, the equipment used to measure float current accurately used complex analog electronics and required precise calibration.

A method for reading float currents, often employed is an inline shunt. A shunt is a linear resistor that drops a voltage directly proportional to the current flowing through it. One drawback behind the installation of a shunt is that the battery circuit must be opened for installation. A second drawback is the shunt must be sized for the maximum current draw. Take the following scenario, a load requires a constant 100-Ampere current flow at 54 volts DC. The shunt used would drop 50 milliVolt when 100 amps of current flowed through it. A secondary battery capacity may be sized to supply an eight-hour reserve time. A manufacturer may state this battery requires 200 milliAmperes of float current. 200 milliAmperes of current flowing through a shunt rated to drop 50 milliVolt at 100 Amperes of current flow will only drop 0.1 milliVolt. Taking into consideration a shunt's rated uncertainty, the non-linear effects of a current shunt at low currents and the rated measurement uncertainty of the apparatus reading the dropped voltage, the measured data cannot be accurately used in any significant prognosis of battery or system health. The converse would be to use a shunt rated at a 50-milliVolt drop for 200 milliAmperes of current flow. However, when the current requirement on discharge is 100 Amperes, the voltage drop across said shunt would be 25 Volts. Not only would this voltage drop be unacceptable for the load, the energy dissipated by said shunt as heat, would be at the underestimated description, be hot.

Another method, often used for current measurements, is Hall effect sensors. These transducers, when offered in split-core design, typically, do not require that a battery string be opened for installation. However, as with the shunt, if the Hall effect sensor is sized for the current flow of discharge, the accuracy suffers at low float currents. If the sensor is undersized to monitor float currents, potential problems may occur upon high discharge. Some of these may stem from an over-saturated Hall effect core. Also, a Hall effect sensor typically relies on a temperature and noise sensitive analog to digital circuit. These qualities of a low current Hall effect approach contribute adversely to measurement accuracy. A Hall effect sensor, designed to monitor small currents on a high current power system, soon becomes too costly in design elements alone not to mention the possible addition of compensating circuitry and unconventional material cores.

All of these negative factors against the potential benefits, weighed by an end user balanced toward a decrease in interest for utilizing float current as a parameter in determining battery health.

It has been very easy for a service provider to monitor failures of other equipment within the standby power system. Event occurrences are characterized as either failed or operating. The electronic and mechanical equipment within a standby power system responds well to event signals defining whether something is working.

However, as pointed out within this article, it is very difficult and very expensive to provide such an easy forecast into battery reliability.

Some research indicates that even with the maintenance schedule outlined in the IEEE 1188, a premature capacity loss due to an unpredicted failure mode can occur without ever being recognized. Add this to today's fact that such a thorough maintenance routine performed quarterly is an expense that most end users skim, and the benefit of monitoring float current becomes more appealing.

The three main criteria for implementing the use of a sensor technology are, first, the cost, second, the ease of use, and third, the amount of data that needs to be analyzed. With an inexpensive, easy to use, simple float current probe (Multitel FCP-01) permanently installed on a battery string and connected into a network surveillance system, a window into accurately reporting a potential battery problem is created. By allowing the internal processing unit of the float current probe to observe the float current trending, monitoring battery failure can be easier. The simplicity approaches the event monitoring for other equipment within the standby power system.

FCP Operation

Multitel's float current monitoring and reporting is done via a non-intrusive sensor technology that can be installed permanently into a system. The installation is quick and does not require opening a battery string. Also, there are not any introductions of components that can become a single source of failure. The measurements and reporting are done continually and in real time with a computation being reported periodically. The probe also analyzes a limited amount of trending data and provides a simple form C dry-contact output alerting surveillance centers to the onset of battery problems.

The float current probe relies on a special split core transducer that surrounds a conductor. Periodically, every few milliseconds, the transducer core is reset and the secondary current immediately after the reset pulse is measured[8, 9]. The secondary current measured, of course, is directly proportional to the primary current present. The core becomes subject to another relaxation or reset pulse and the cycle begins again.

A physical core, large enough to accept typical conductors, sized for a full battery discharge and recharge, will have inverse effects on the low end scale of current sensing due to losses in the core. Also, the reset current pulse amplitude limits the range of the core.

Using a saturable reactor oscillator principle can alleviate some of the above uncertainties. Generating a given current within a core's winding in addition to the magnetic flux generated by the current carrying conductor, provides an overall flux that after a certain amount of time will reach a saturation point.

The time to reach saturation is a function of the initial flux density. The time depends specifically, with a constant, regulated voltage applied to a core's winding, on the magnitude and direction of the DC current sensed in the surrounded current carrying conductor as characterized by the Gauss Law for Magnetism[10]. If the flux produced by the sensed current is opposite the flux generated by the ferrite core winding voltage, the time to saturation will be longer.

Small current measurements, using the above logical concepts, are plagued by external influences. A few are:

- Temperature
- Noise
- External magnetic fields
- Internal core magnetic fields
- The resistance of the core winding within the saturable reactor oscillator.

External shielding helps. Also, by utilizing a shrewd method of data gathering and statistical manipulation, external influences do not necessarily have to increase the signal to noise ratio. Triggering the voltage application, and therefore current generation, to the core by a digital switch, and precisely timing the opening and closing of said switch can realize a measurement differential. This differential is without the curse of external conditions and is directly correlated to the current in the surrounded conductor. Future testing of this technique shall provide data outlining to what degree these ambient factors influence the actual current measurement.

This data, stored in digital format, is available for the end user through a low-impedance over-voltage protected 50-milliVolt output. This is executed by a digital to analog circuit. The raw digital data, theoretically, can be exported to a higher end monitor that accepts a digital input. This would be the ideal scenario for ultimate accuracy. The 50-milliVolt output, however, allows the probe to interface with any monitoring system that has the ability to monitor a traditional shunt. Also, this output provides a measurement for recording that is easily accessible for routine inspection teams. This output is valuable, as well, for maintenance teams called by network surveillance personnel. This parameter is a key factor when there is an indication of battery trouble. The measurement requires a voltmeter with a scale that can measure a 50-milliVolt signal. Typically, this is standard equipment for the above-mentioned teams.

By having the data computed in a digital format, the probe can go a step further and analyze trending to provide the user with an event output. Some specific alarms that can be identified by the probe include:

- Open string
- Low Float Current
- High Float Current
- Battery on Charge
- Battery on Discharge

This ability saves on the requirement of real time continuous analysis of useless data by a service provider. This event alarm signals when a battery plant problem would need further investigation.

Battery trending

There are factors affecting a battery plant's float current requirement. First, it is necessary to understand the steady state behavior of a battery plant floating on a constant voltage charger[11, 12].

A battery is not a linear device. The ratio of the voltage to current is not constant as for a resistor. Increasing a battery's voltage above the open circuit potential will result in an increase in float current in accordance with Tafel curves. For instance, in a VRLA battery cell, the float current becomes largely a function of temperature and polarization. Polarization can be determined, in the case of the VRLA battery, by applying the Nernst equation, which yields a simple equation for open circuit voltage.

$$\mathbf{V_{OC} = Sp.Gr. + 0.85}$$

Any voltage applied to the cells above this potential specified by the Nernst equation is shared between plates as polarization. In a VRLA cell, it has been presented that there is generally more variability in the behavior of the negative, while the positive behaves more predictably. In a hypothetical single-cell system, the behavior of the negative determines how much polarization is left over for the positive, which in turn determines the float current.

When there is a chemical imbalance, where a cell operates with internal and external conditions being different than the theoretical lab case, the float current becomes a direct indicator as the polarization equilibrium changes[13].

In a VRLA cell, a possible condition has been documented where the initial polarization of a cell causes a small amount of water loss increasing the oxygen transport from positive to negative[14]. The increased recombination efficiency acts to depolarize the negative plate and provide more positive plate polarization. This is characterized by an early increase of a battery's float current requirement with time. As an increased float current is required, water loss increases. This is due to the small but measurable inefficiency in the recombination reaction, and from grid corrosion. The positive grid corrodes at a speed, a direct relation to the rate of the recombination reaction. Corrosion is characterized when lead is converted to lead oxide (oxygen from water is consumed) and hydrogen is produced loosing water from the system. This will increase the electrolyte specific gravity decreasing the amount of net polarization to be shared between plates. The effect is a loss of capacity and a decrease in the required float current. This is a characterization for natural aging. If external influences do not allow an equilibrium between the increased oxygen transport to the negative, grid corrosion and the inefficiencies of the recombination reaction, the cell will have a steadily if not exponential increasing float current. This can be signaled with a measuring device either by the output of real time data or by the issuing of a high threshold event alarm. If the battery ages naturally and the primary failure mode is grid corrosion, a measuring device can be key in determining the ability of a battery plant to retain required capacity.

Also, with the closed loop reaction in a VRLA cell, theoretically no net chemical changes occur. Physics tells us that the energy consumed by supplying a float current to polarize the battery plates must be accounted for. The electrical energy is converted to chemical energy to drive the recombination reaction, which in turn releases the energy in the form of heat. This heat must then be dissipated. Typically the power density within a VRLA cell limits this dissipation and thermal equilibrium cannot be reached. The increase in temperature drives the chemical reactions faster which leads to an increased rate of temperature rise and plate degradation into soft shorts. A continuing scenario can lead to thermal runaway. Again, a measuring device would be matchless in detecting the above scenario before irreversible damage was sustained an investment lost.

Many solutions for slowing the negative depolarization have been incorporated either directly into a battery's design or indirectly into how a battery is charged. An example that resourceful battery manufacturers employ are internal catalysts that recombine oxygen back into water without being part of the recombinant reaction at the negative plate[15, 16]. This author believes that these catalysts act to increase proportionately with the concentration of free oxygen, to a limit based on the amount of catalyst included within the cell, a secondary reaction of oxygen and hydrogen into water. This slows down the recombination reaction which serves to polarize the negative and depolarize the positive, reducing the float current required, reducing the positive grid corrosion and reducing the possibility of thermal runaway. Another example is to compensate with a decrease in charge voltage to an increase in temperature. By reducing the charge voltage, the amount of voltage split as polarization between the negative and positive is reduced and therefore the required float current to maintain the polarity is less. These failure-deterring methods, as well as others, can be monitored with the addition of a float current probe.

Another link to float current can be made in vented lead acid batteries. In this case, if all goes well, float current will steadily decline as active material degrades and the overall electrochemical reaction slows. Then, a monitored low float current can determine the end of battery life.

Additional failure modes occur when the water level drops below the level of the plates. Active plate material involved in the electrochemical reaction is reduced. There is therefore an increase in the reaction rate per physical unit area of plate. This increased reaction rate, similar to the same scenario in a VRLA battery, can be a precursor to thermal runway or dry-out in a vented lead acid battery. The increased temperature is accompanied by an increased float current requirement necessary to maintain a constant voltage. The author believes that this too is a failure mode attributable in the vented ANC batteries. This failure mode would be reported by a measured increase in float current. This can signal maintenance before the failure mode becomes dangerous.

In a vented lead acid cell, there is also a possibility of sedimentation leading to soft shorts. In an ANC battery, there is the natural chemical aging process called cadmium migration across the plate separators. This, also, leads to soft shorts. Soft shorts, with a constant voltage charger, can be easily identified by an increase in float current. A float current device, registering an increase in float current, can signal the required maintenance.

Finally, external system variables may affect a battery's requirement for float current. For instance, two high of a float voltage will increase the voltage available for plate polarization and therefore increase the float current. This high float current, sensed by a float current measuring device, can quickly indicate a condition where a battery will age prematurely. This scenario has similar circumstances with an increase in temperature. Battery manufacturers have specified float voltage ranges and temperature ranges that their batteries are designed to operate within. The float current probe then becomes a device to pinpoint potential system problems as well as battery problems.

Defining Thresholds

The probe triggers a form C dry-contact relay closure based on current thresholds and logical arrangements of events. Two methods of thought have been incorporated with respect to the trending criteria for threshold realization.

The easiest to identify is when the battery plant is on recharge or discharge. This is characterized by primary and secondary criteria that must be utilized to remove nuisance alarms. The primary is a large current flowing through the conductor. The secondary is a high rate of change of the amount of current flowing through the conductor. The probe can easily determine if the current flow is out of range. The probe can also determine the direction of current flow characterized by a battery being on discharge or on recharge. What is important is that the probe also can detect a high rate of change. This will alleviate the situation where the battery has just gone on discharge and the current momentarily crosses the "low float-current" threshold but has yet to go out of the probes range. This is especially critical when the alarms are latched. This small condition, if not corrected for, can cause a maintenance team to be called for a normally operating standby power plant.

The more difficult is the threshold selection for "low float current" and "high float current" especially for VRLA battery cells. It has proved difficult, if not impossible, to have the battery manufacturers to agree on thresholds related to cell ampere-hour ratings. Although the theories of cell operation and the electrochemical reactions are the same, one manufacturer's threshold still differs from another.

Two approaches are being looked at. The first is to have hard thresholds either user selected or preprogrammed at our factory corresponding to the actual manufacturers data for the particular cell model and size. The second is to follow a statistical study of optimized efficiency and utilize non-dimensional units to determine thresholds. For instance, if a battery-cell's required float current has decreased to 50% of its nominal value, a statistical study may show true an assumption that all cells have a failure probability greater than 50%. Or if a battery cell's required float current has increased by a factor of four over its nominal value, then a different failure mode may have be encountered increasing a cell's probability of failure above 50%.

These thresholds can be extrapolated into an oversimplified linear probability of failure relationship. An example follows:

Let FC be the nominal float current.

Let fc be the measured float current

Finally, let $\%$ be the probability of failure

$$\text{If } \frac{fc}{FC} \leq 1 \text{ Then } \% = (1 - \frac{fc}{FC}) \times 100 \text{ Else}$$

$$\% = \frac{1}{4}(\frac{fc}{FC} - 1) \times 100$$

Also, secondary criteria with rate change as a parameter could be incorporated to outline any abrupt changes in float current.

The continuing trials of prototypes, the logging of test data, as well as how the market requests the product, will determine which approach, if either, is used. Also, if the statistical study is the preferred method, intense testing must follow to define better a probability of failure relationship. Perhaps a new finding will be incorporated for more accurate results. Any simple threshold relationship can be implemented on the existing product platform. It is only the software that changes.

Finally, there is a parameter to acknowledge unit fail. CPU fail can be restarted internally by a watchdog circuit. However, when the unit fails consecutively for a set number of times, an external alarm must be activated.

These alarms, in concept, will be issued via a latching summary alarm. The probe would have to be reset locally. Whether the alarm latches or not is defined by software. Tri-color LED indicators on the unit will define the actual threshold that has been violated or condition that has been sensed.

Conclusion

The required float current, to keep a cell at a constant voltage is a parameter that can provide a window into any battery, as to its state of health. With the innovative technique this author describes, a usable float current measurement device can have the following design elements:

- An inexpensive cost
- a small package
- a non-intrusive design
- easy to install
- easy to operate
- accurate
- temperature immunity
- noise immunity
- flexible for various applications

Besides having an active tool for accurately measuring float current, the described technique allows the capability to utilize clever algorithms to analyze and trend data. This allows a service provider to maintain and assess batteries reliably before any serious condition exists that may jeopardize the ability of the standby power plant to operate when needed. Although not the deciding factor to replace or repair a battery string, the float current probe will bring a new light into when a battery plant requires inspection by a technician. Or, the float probe can indicate when a battery plant needs to be monitored more closely. The flexibility of the design allows either stand-alone operation, or the ability to add a float current measurement to any system.

This author strongly emphasizes that a battery's required float current, to maintain a given polarity, must be investigated further. The technique utilized to measure small currents in large current capacity systems, needs to be investigated further as well. Data gathered from field trials combined with data gathered during in-house testing would cultivate a more developed understanding of the devised measurement technique, as well as, verify the importance of the float current measurement. Future papers will justify these topics and outline more innovative ways to utilize the float current measurements.

References

1. R.K. Jaworski and J.M. Hawkins, "Thermal Runaway behavior of VRLA batteries", Proceeding of Intelec '96 (1996).

2. J.A. Marrero, "Determining Availability of Lead-Calcium Batteries Using Charging Current", Proceedings of the 1st BattCon, 1997, Paper 8.

3. W.P. Cantor, E.L. Davis, D.O. Feder and M.J. Hlavac, "Performance Measurement and Reliability of VRLA Batteries – Part II: The Second Generation", Proceeding of Intelec '98 (1998), Session 16, Paper 3.

4. W.E.M. Jones and H.A. Vanasse, "Can VRLA Batteries Last 20 years?", Proceeding of Intelec '98, Session 19, Paper 4.

5. T.H. Sloane, "Powering Costs as Fiber Goes Deeper Into the Loop", Proceeding of Intelec '98 (1998), Session 12, Paper 3.

6. O. Vigerstol, "Advanced Nickel Cadmium Batteries for Telecom Applications", Proceedings of the 2nd BattCon, 1998, Paper 9.

7. E. Davis, D. Funk and W. Johnson, "Internal Ohmic Measurements and Their Relationship to Battery Capacity", Proceedings of the 2nd BattCon, 1998, Paper 2.

8. R. Sevens, "Improving and Simplifying HF DC Current Sensors", Proceedings of the 1986 IEEE

Applied Power Electronics Conference (APEC '86), pp. 180-183

9. A. Radum and J. Rulison, "An Alternative low-cost current-sensing scheme for high-current power electronics circuits", Proceedings of the 1990 IEEE Industry Applications Society Annual Meeting, pp. 619-625

10. P.M. Fishbane, S. Gasiorowicz and S.T. Thornton, Physics For Scientists and Engineers, Prentice Hall, Inc., 1993, Chapter 24

11. Z. Noworolski, "Dynamic Properties of the Lead Acid Battery", Proceedings of the 2nd BattCon, 1998, Paper 15.

12. D. Calasanzio, M. Caselli and J. McDowall, "Understanding VRLA Charging and Other Operational Characteristics", Proceeding of Intelec '94 (1994), Session 6, Paper 4.

13. J. McDowall, "Avoiding Pitfalls of VRLA Battery Charging", Proceedings of the 2nd BattCon, 1998, Paper 12.

14. F.C. Laman, C.S.C. Bose and S.R. Dasgupta, "Accelerated Failure Testing of Valve Regulated Lead-Acid Batteries Using Gas Studies", Proceeding of Intelec '98 (1998), Session 4, Paper 1.

15. B. Dick, "Float Control of the Negative Plates in VRLA Batteries With the MAXIMIZER™", Proceedings of the 2nd BattCon, 1998, Paper 8.

16. W.E. Jones and D.O. Feder, "Correcting Inherent Imbalance and Consequent Failure of VRLA Cells by the Use of Catalysts", Proceedings of Telescon '97 (1997).