AN INNOVATIVE DIGITAL CURRENT MEASUREMENT TECHNIQUE – PART TWO

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ABSTRACT

In a typical standby power application using constant voltage battery charging, float-charging current flows through battery strings to maintain cell polarization. Previous technical papers have described that measuring these small currents is a very effective way to detect thermal runaway and other predominant failure modes, at the root. In addition, previous papers have presented that these float charging current measurements possibly pinpoint failures of other components within the standby power system.

This paper verifies, by introducing experimental field data from an actual application, behaviors that previous technical papers have presented as theory, lab observations, and/or field data. As well, to obtain the field data from an actual application, the author installed a low cost probe based on a specific 'digital measurement technique (DMT)'. Through in-house tests, the low-cost probe was compared experimentally with other proven technologies applicable for measuring the small flow of float charging currents.

This paper, further, attacks the next level of automatic float charging current measurement analysis. Using in-house lab experiments and reasoning, methods for determining the authenticity of a monitored alarm will be investigated and discussed. Various methodologies to determine whether a condition or trend of changing float-charging current is part of the normal battery string operation or the onset of a potential problem will be presented.

As a conclusion, this paper examines, in actual application versus theory, the cost versus benefit of monitoring the float charging currents in a standby power system and proves its overall viability for a worst case application. This conclusion is based on the cost/benefit properties found when using a low-cost probe based on the DMT.

THE DIGITAL MEASUREMENT TECHNIQUE

The probe used to measure the float charging current in the actual field application uses a DMT. A DMT has some particular design characteristics. These include, but are not limited to the following: non-intrusive installation and monitoring and no affect by temperature, probe orientation, external magnetic effects and noise insusceptibility. Alone, these design characteristics lend themselves to a valuable probe to have in the field. Also, there is little cost when implementing a DMT. Further, add in the benefits of a DMT probe found when compared with other current sensors. The feasibility of monitoring the float charging current, out in the field, with a probe based on a DMT, is viable for a typical battery user.

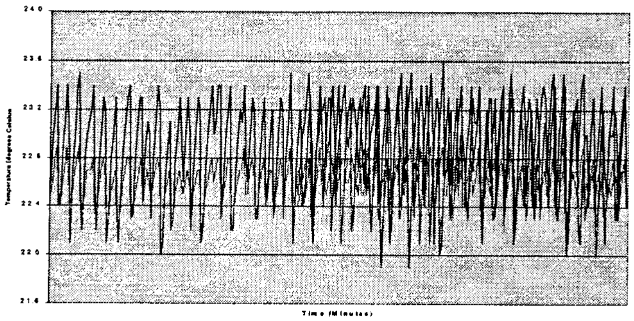
A final important note: the manufacturer had an unbiased representative quickly install and verify the operation of a DMT-based probe. When incorrectly installed, the DMT-based probe does not operate. Verification is therefore straightforward.

The DMT relies on a simple split-core transducer that surrounds a conductor. Periodically, the transducer-core resets and the secondary current immediately after the reset pulse is measured. The secondary current measured, of course, is directionally proportional to the primary current present. The primary current is the current flowing through the conductor. The core becomes subject to another relaxation or reset pulse and the cycle begins again.

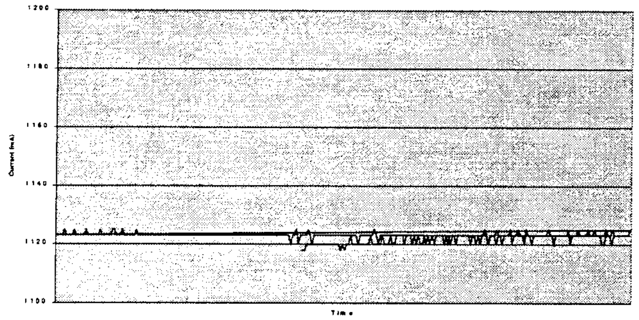
Using these logical concepts, external influences plague small current measurements: temperature, noise, external magnetic fields, internal core magnetic field, and the resistance of the core winding within the saturable reactor oscillator.

By using 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 its opening and closing, all while maintaining the overall core at zero flux, can realize a measurement differential. The current in the surrounded conductor directly correlates to this differential without the curse of external conditions.

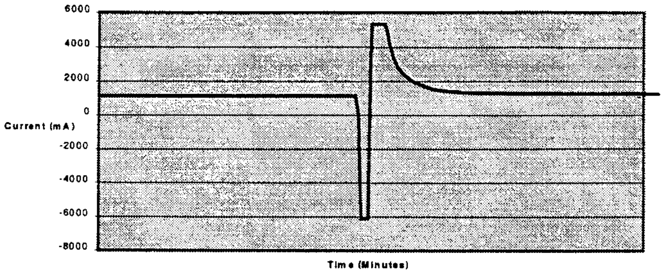
Graph 1 – Battery and ambient temperature in actual field application



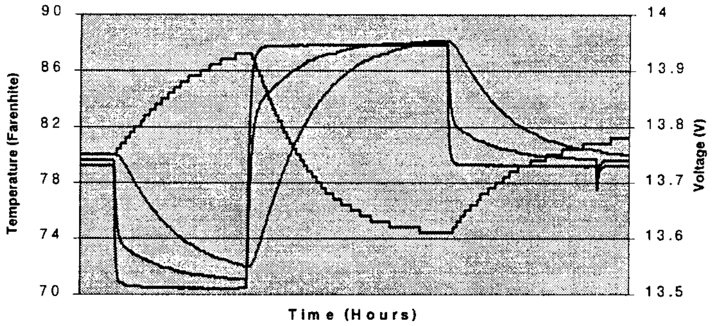
Graph 2 - Float charging current in actual field application



Graph 3 - Discharge and recharge in actual field application



Graph 4 - Temperature and voltage versus current



Data is stored in digital format. The data is transformable, as an output, into both analog and digital forms. In addition, inexpensive components manipulate digital data. Mathematical algorithms analyze and trend digital data. Raw data converts into specific alarms (e.g. battery on discharge, over current, etc.) This ability saves on having real time continuous analysis of useless data by a service provider. A device triggers an alarm when a battery needs further investigation.

A FIELD APPLICATION OF THE DIGITAL MEASUREMENT TECHNIQUE

DMT based probes are installed in the field. Float charging current measurements and other measurements on a real time basis including, but not limited to, ambient temperature and battery temperature and voltage are recorded. Events including, but not limited to, AC failures and battery discharges are recorded as well. The application with the most data available to present in this paper is a Bell Canada site located in Quebec City. The application is in an above ground walk-in enclosure. The probe is attached to a single string of 900 Ah batteries.

The ambient and battery case temperatures vary throughout the day depending on the environmental control system's operation. See graph 1. The placement of the environmental control system within the confined quarters of this walk-in enclosure affects the battery string temperature probe. Ambient temperature varies quite drastically, also because of the cycling of the environmental control system.

The correct installation of the site' temperature probes were verified. In some sites, however, installers had not properly installed a temperature sensor on the post or on the case of the battery, depending on the particular temperature-probe configuration. See pictures 1 through 6.

A possible and likely conclusion is that in many 'real world' confined space applications; temperature sensors may not be as accurate as in the testing environments. As shown here, in an application that is not as confined or cramped for space as a majority today's, cyclic environmental changes affect the response of ambient and battery temperature sensors. This is especially true when the environmental control system is positioned within the confined quarters of a site that inadvertently heats or cools the surfaces monitored by temperature probes. Multiply this shortcoming with the even larger issue of the many applications with badly installed temperature sensors.

The rate of reactions within a battery cell is a function of temperature. Furthermore, the recombination reaction in VRLA batteries liberates heat. As the temperature and the rate of reaction increase, more heat is produced. If the rate of heat production overcomes the ability of the battery cell to dissipate the heat, a condition occurs where the temperature of the cell drives an increase in current consumption which, in turn, drives to increase the temperature of the cell further. The current limit of the charging system clamps the electrical energy influx. Because the charging system is sized such that a battery can be brought from deep discharge to a charged state within hours, there is plenty of electrical energy available to fuel an unbalanced battery. This chain of events occurs exponentially. This is more commonly known as thermal runaway. This is why temperature sensors are used.

Charger manufacturers use temperature sensors with either delta or absolute algorithms to monitor battery conditions and issue battery alarms. Further, some manufacturers use temperature sensors with algorithms to control the voltage potential the charger applies across the poles of a battery. This compensates the temperature change with an inverse voltage change to keep the reaction rate within the design limits of the battery cell.

Charger manufacturers realize these benefits in laboratory settings, but with evidence from this particular site, temperature sensors may not give the best data to these built in algorithms. From the data collected, the worst case, in our applications would be the delta-alarming algorithm. The delta temperature recorded changed drastically because the sensor was installed close to the environmental system's output. In this case, a real alarming situation is difficult to determine. Further, because the environmental system influenced the sensors located on the case and posts of the battery cells, a possible conclusion is that temperature is less dependably measured in the close confines of today's sites.

Users increase thresholds to only alarm when a real event is occurring. This, in effect is a way to cancel out false alarms. A possible problem is when the monitoring system finally detects a real alarm the exponential chain of events has gotten to near-catastrophe and a user must handle it as an emergency.

Finally, there is evidence that installers are not correctly implementing temperature sensors in the field. Most commercially available temperature sensors will not alert if an installer has incorrectly implemented them in the field.

The float charging current measurement is a direct indicator of the internal reaction rate of a battery. As seen from the site data, there is no detectable change in the float charging current measurement. See graph 2. The environmental control system's cycles did not affect the internal reaction rate of the battery as drastically as the temperature sensor would have a user believe. The alarm provision personnel can tighten the thresholds or methods for determining an alarm when monitoring a float charging current measurement versus a temperature measurement, without inducing false alarms. The scientific community calls this having a greater signal to noise ratio.

It is important a float charging current probe withstand the large current flow of a cell discharge and a full cell recharge. The author captured such a discharge and recharge event at the field test site. See graph 3. An inherent quality of the DMT is that when out of range, the output simply hits a numerical limit. When the measurement comes within range, the technique will again output the correct current.

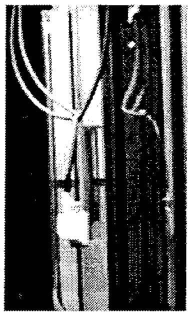
Finally, a DMT-based probe' installation is performed quickly and, if incorrect, the device does not operate. Unlike temperature sensors that will output a temperature whether installed correctly or not, the DMT does not work unless installed correctly.

AN EXPERIMENTAL COMPARISON OF TEMPERATURE AND FLOAT CHARGING CURRENT

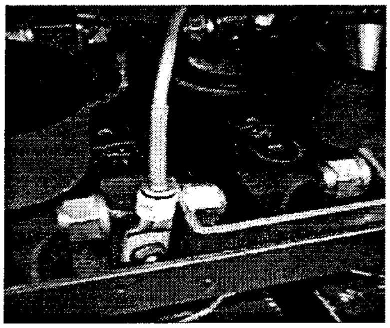
The author mounted temperature sensors on the battery case and the positive and negative terminals of a mono-block. Also, a probe was inserted and sealed within the cell to measure the electrolyte temperature near the surface of the plates. Finally, the lab-calibrated power supply was limited to maintain a constant float charging current. The battery voltage was monitored on a lab-calibrated digital voltmeter. The battery was valve-regulated lead-acid (VRLA) with a nominal rating for the string of cells measuring 12 V and a capacity of 60 Ah.

The reaction rate was maintained by the constant current charger while the ambient external environment temperature was varied. The three external battery' temperature sensors followed the ambient environment temperature. The internal temperature sensor was slower to react to the effects on the ambient environment temperature. After hours of equilibrium,

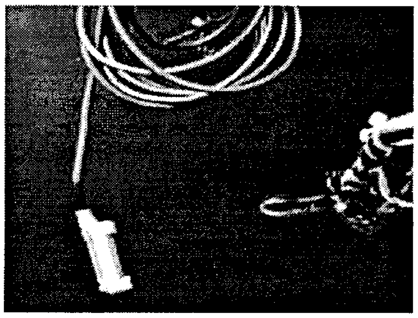
Picture 1 – Poorly installed jar temperature sensor



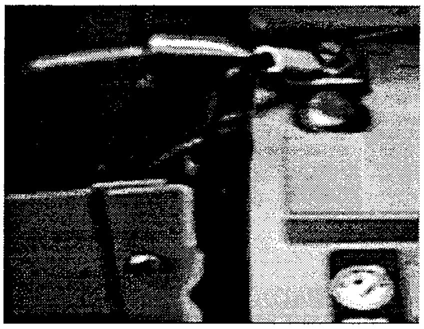
Picture 2 – Correctly installed post temperature sensor – flooded cell



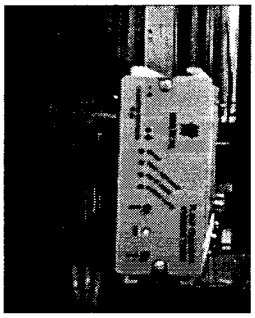
Picture 3 – Poorly installed ambient temperature sensor



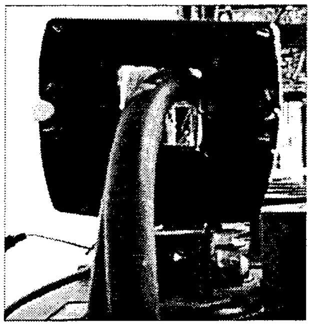
Picture 4 – Correctly installed post temperature sensors – VRLA mono-block



Picture 5 – Digital measuring technique – control unit



Picture 6 – Digital measuring technique – sensor head



the temperatures would synchronize. However, the 'noise' measured by the temperature sensors mounted outside of the battery was greater than the internal temperature of the battery cell's. See graph 4.

The voltage across the battery poles and the internal temperature measurements related indirectly. The experimental data showed that a change of a few degrees in temperature measurement equaled a large change in voltage measured. This change can be easily understood by considering the exponential relationship between temperature and charge current, and between charge voltage and charge current. With typical equipment deployed in the field today, changes in voltage can be measured much more accurately than changes in temperature.

Batteries, typically, do not come with internal temperature sensors. The signal to noise ratio of measuring the float charging current versus measuring a battery temperature from outside the battery case is higher. Further, with current technology, the measurable degree of float charging current change is larger than the temperature change when the reaction rate increases.

The DMT for measuring float-charging current has a high resolution and accuracy of measurement. A temperature measurement device, available for use in mass deployment, is typically low resolution and low accuracy. The DMT itself, compared to the temperature measurement technique deployed today has an inherent increased signal to noise ratio. The failure mechanisms trigger catastrophic battery events, like thermal runaway, exponentially. In real terms, using the DMT to monitor the float charging current will provide an exponential increase in time before catastrophe. A user can identify and handle a battery cell problem without it being an emergency.

AN EXPERIMENTAL COMPARISON OF OTHER METHODS FOR MEASURING CURRENT

The author monitored current with four sensing devices: a calibrated lab-quality constant-current power-supply, a Hall Effect sensor, a shunt, and a DMT-based probe. When setting up the experiment, scenarios were recreated to best simulate actual field situations. For each measurement type, the method of acquiring the measurement value, its accuracy and the repeatability of getting the same values on subsequent trials is described.

The values for a typical 900 Ah battery-string where especially focussed on. A user can reliably expect to keep a 75 A load on-line for eight hours with a 900 Ah. The average float charging current of a new 900 Ah VRLA battery was assumed to be between 200 and 900 mA. The current measured by the lab-quality current source was varied from zero to one amp using steps of 100 mA and then one to five amps using 400 mA steps.

Also, further experiments injected AC into the constant current line. Two scenarios where simulated, a constant AC injection with a varying DC current and a proportional AC injection with a varying DC current. The DC current was varied from zero to five amps similar to before. In one trial a constant 300 mA of AC current was injected and in a second trial, a proportional AC current equal to 10% of the DC current at any given time was injected. 60 Hz was the AC frequency. The author recorded the same data as before including the time needed to get a stable result.

The Shunt

A '50 mV equals 150 A' shunt was used. To install the shunt the circuit was broken. In the field, this would require special precautions, especially in single-string applications. The shunt was secured in a bus bar configuration. An alternative to the hard bus configuration could be a special shunt with an insulated mounting base secured to a stable surface. In this application, a cable would be broken and re-lugged, and the shunt cabled into the circuit. The physical size and strength of a shunt limit the number of lugs that can actually be landed on its terminal blocks. The shunt itself is rather inexpensive, but its installation into a battery string, if not done at the battery manufacturer's facility or during the initial installation, could prove very costly.

In setting up the shunt in the experiment, shunt was expected to drop voltage from zero to 1667 microvolts. A calibrated digital voltmeter was used with a μV measurement scale and a moving average option, similar to models used in the field by battery technicians. See graph 5. The data became more accurate and consistent over the three trials as the current increased to five amps. Between 200 and 900 mA the data's accuracy and consistency was poor. However, the data could be consistently trended to determine relative differences.

With the AC current held constant at 300 mA, the data became more accurate and consistent as the DC current increased to five amps. It took less time for the measurements to stabilize as the DC current increased. Between 180 and 900 mA, the values were not accurate or consistent. The stability time was up to seven minutes. With the AC current proportional to 10% of the DC current, the stability time was consistent at seven minutes throughout the scale of current measurements. The accuracy and consistency of the reading resembled the data found from the DC current trial alone but with a greater standard deviation of readings. See graphs 6 though 8. With AC injection, the delta change in measured values is not consistent. This means that if a system has any AC component, the worst being AC proportional to the DC current, trending data becomes almost impossible without large swings in the float charging current. This counters the inherent benefit of increased signal to noise ratios.

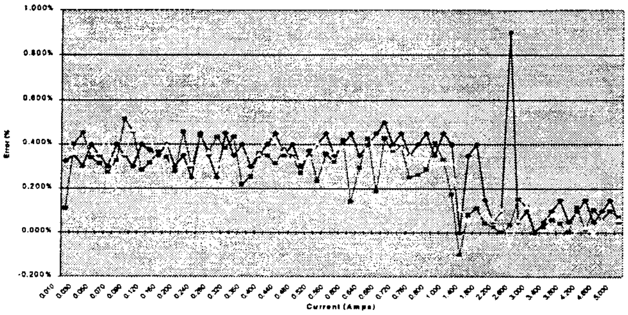
The Hall Effect Sensor

The Hall Effect sensor was calibrated as per the instructions to measure up to 100 A. The Hall Effect sensor requires an exact excitation charge to activate it. In the lab experiment, a lab-calibrated current source supplied the exact excitation charge. In the field, to be cost-effective, a scaled back power supply is required to excite of the Hall Effect sensor. This power supply needs internal compensation to remain constant when affected by environmental factors. The Hall Effect sensor-head has a split core configuration that slips over the conductor to be monitored. Precautions were taken to place the conductor exactly perpendicular to the face of the sensor. Any change in orientation requires a change in calibration.

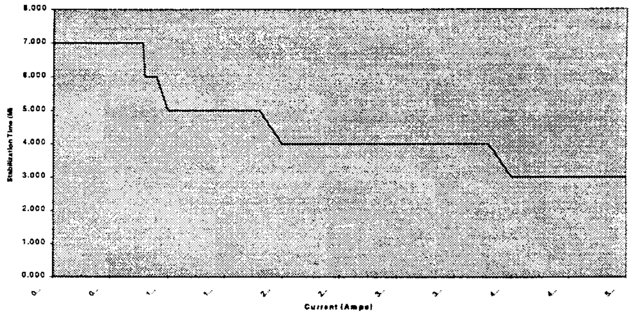
The Hall Effect sensor was more consistent and accurate than the shunt. As the current increased, so did the consistency, while accuracy decreased. See graph 9. The Hall Effect Sensor was much more tolerant to the experiments with AC injection showing tighter measurement grouping. The trending accuracy was much higher with the Hall Effect sensor. A change in the current measurement could be consistently identified for trending purposes. See graphs 10 through 12.

The Hall Effect sensor is extremely sensitive to temperature changes. When a temperature change similar to which affected the string in our field test site was simulated, the Hall Effect sensor became unstable. No measurement was possible at this time. After the sensor head reached an equilibrium temperature throughout, the current measurement was again stable but with an offset.

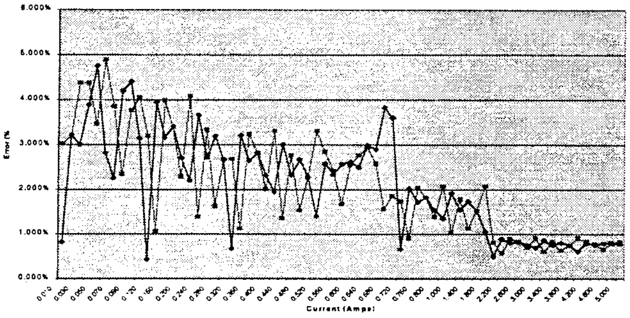
Graph 5 – Constant DC with shunt



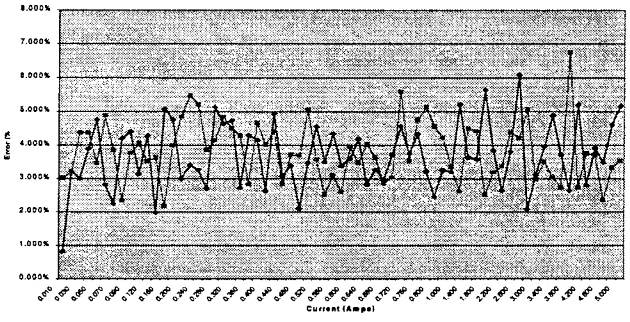
Graph 7 – Stabilization time with shunt



Graph 6 – Constant AC with shunt



Graph 8 – Proportional AC with shunt



The orientation of the Hall Effect sensor was modified with respect to the conductor. The readings became very unstable. Upon regaining equilibrium, the sensor also regained a stable current measurement. The current measurement, however, was not the same as before modifying the orientation. The temperamental operation of the Hall Effect sensor coupled with its inaccuracies and high acquisition cost make it an unlikely candidate for the small confined sites of today.

A small-current Hall Effect sensor was not tested with this exercise. The manufacturer's data sheet that accompanies the Hall Effect sensor describes a maximum current. There is no inherent property within a Hall Effect sensor to degauss itself. If a larger current than specified by the manufacturer flows through a conductor the sensor is around, permanent damage will result. The confidence that permanent damage will occur and the severity of such damage is directly proportional to the amplitude and period of high current flow through the conductor inside the sensor head. Float charging currents are 100 to 1000 times smaller than discharge currents. A discharge of this magnitude would permanently damage a small Hall Effect sensor capable of measuring very accurately the float charging current.

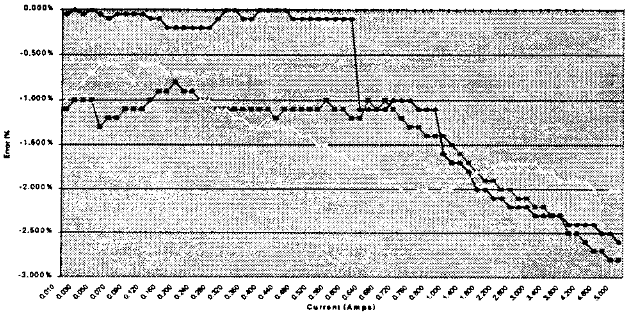
The Digital Measurement Technique

The low-cost DMT based probe, equipped with a digital electronics' power supply, required a voltage power input of 18 to 60 V D.C. The device uses a split core sensor head. Installation does not require breaking the circuit. The probe acquires the measurements in digital format. Using digital signal processing the probe rejects AC.

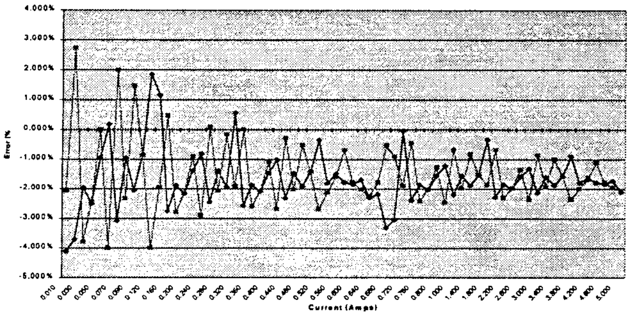
The technique takes various measurements and converts them into digital encoding. Values are compared and errors are canceled out. There was no appreciable spread on measurements at low or high currents. All measurements where within a small standard deviation and repeatability was constant. See graphs 13 and 14. The probe required two minutes to stabilize. The moving average feature on the digital voltmeter was disabled. The probe output was calibrated to five amps equaling 50 mV. The output was measured using the standard mV scale on the digital voltmeter.

The probe computes the current using digital means and stores it as a digital number. An over current happens when the probe reaches a set integer. A clamped operating range was discovered. The sensor head inherently degausses itself after every current measurement. A current flowing through the sensor head, whether within the operating range or not, does not affect the overall system. This means the DMT operates in the clamped current measurement range and is idle outside of that range, regardless of current amplitude.

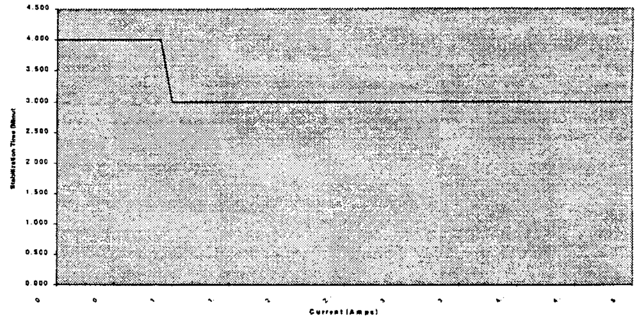
Graph 9 – Constant DC with Hall Effect



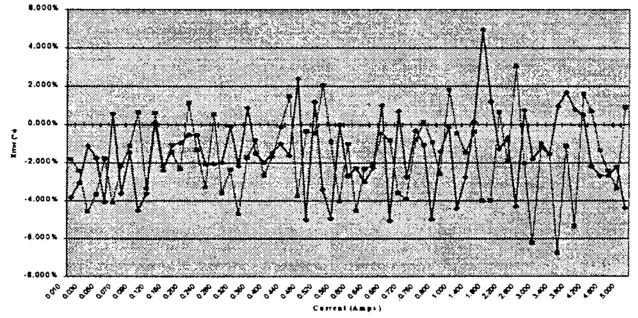
Graph 10 – Constant AC with Hall Effect



Graph 11 – Hall Effect stabilization time



Graph 12 – Proportional AC with Hall Effect



PROCESSING DATA USING THE DIGITAL MEASUREMENT TECHNIQUE

The DMT interprets the float charging current as a digital number. It can manipulate, with mathematically encoded algorithms, the values to get useful alarms. Analog techniques require intricate and precise manipulation to accomplish the same.

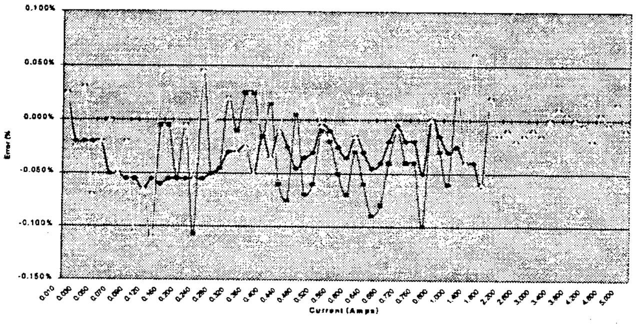
Two methodologies for triggering alarms are discussed that resemble the thought process of a technician when analyzing raw float charging current data. The first methodology compares the float charging current measurement to failure criterion for a particular battery type. The second methodology watches the float charging current measurement over time, monitoring closely any trends that develop. For the technician and the DMT it is easier to use the first method rather than the second.

The Absolute Comparison to a Defined Failure Criterion

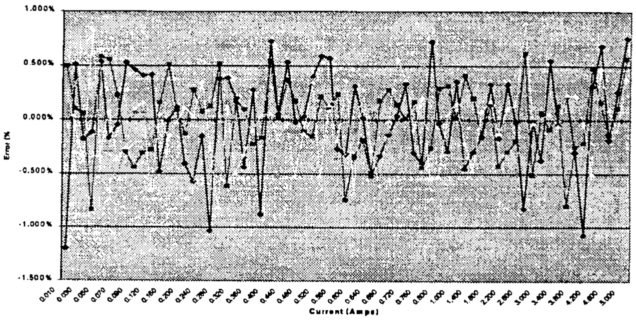
The challenge of the first method is determining the failure criteria. A battery design fixes the chemical reaction rate based on the charging voltage potential and the temperature. As a battery ages, the mechanical, electrochemical and electrical properties change and so, too, does the chemical reaction rate in accordance. Measuring the float charging current directly indicates the chemical reaction rate.

A probe based on a DMT has a high signal to noise ratio. Because of this, the threshold for too high a float charging current could, theoretically, be tightened to a factor between one and a half and four times the nominal value for new cells. This could be done without fear of generating false alarms when battery cell is only behaving as expected. Although between one and a half and four times the float charging current seems like a large increase, this only accounts for a little less than double to quadruple the reaction rate inside the battery cell. The typical design limits of a battery cell allow this increase in reaction rate without an appreciable buildup of temperature buildup. However, this trend is identified as a precursor to future problems. In a thermal runaway scenario, the strings of events that act upon each other are exponential. The probe based on a DMT identifies these events very early in the scenario allowing more time to respond.

Graph 13 – Constant DC with DMT-based probe



Graph 14 – AC with DMT-based probe



With the DMT exhibiting a high signal to noise ratio, the criteria for cells with too low a float charging current could be tightened to a factor of one-half to three-fifths the original value when the cell was new. Too low a float charging current at a constant temperature and polarization may indicate a loss of capacity.

These assumptions of high and low current thresholds vary based on particular battery designs warranted and marketed by manufactures as their product. Although theoretical over and under current thresholds may be useful, without backing by the battery manufactures, the values are useless. The values determined experimentally and recommended by the battery manufacturers carry the most significance. These recommendations have the support of the manufacturer when the float charging current identifies a problem.

Nuisance Alarms Cancellation in an Absolute Failure Criterion Scheme

In a real application, a battery cell may not be maintained at a constant temperature with a constant voltage across its poles. Thresholds recommended by a battery manufacturer, typically, are accurate only for a battery held at a specific temperature and charged to a specific voltage. These thresholds are useless in a system where the charge voltage changes or where the temperature is not regulated. It is difficult to determine problems in a dynamic system using absolute comparisons.

To remove nuisance-alarms caused by a dynamic system, the assumptions are that all the predicted steady-state current measurements of a battery are within the predefined upper and lower current thresholds, secondary current thresholds set the boundaries that signify normal no-alarm recharge and discharge events, and standby power systems return charge equilibrium in a given time. False alarms are controlled by setting a range that is neither too small nor too large between the alarm / no-alarm boundaries of the primary and secondary thresholds. When the measurement enters the alarm range, a timer is set and allowed to count down. Whenever the measurement leaves the alarm range the same timer is reset. All alarms are masked until the timer counts all the way down.

A Trending Scheme

Trending, the second method for generating an alarm is more accurate at determining problems. Trending is monitoring how stable charge current is over time. A charge current that is progressively increasing alerts to an increasing potential for catastrophic failure like thermal runaway. Theoretically, a perfect battery cell's charge current would remain stable throughout its life. In a typical VRLA cell, however, we might see the stability disrupted by the reaction rate increase after first installation, as the recombination reaction becomes more efficient and then the decrease as the plates corrode. Physical factors of the processing strategy used to implement the DMT, however, limit the success of automatic trending.

Dynamic Temperature Cancellation

With the use of more confined locations (e.g. cabinets, CEV's, walk-in huts) ambient temperatures are not reliably constant. A derivation of the Arrhenius equation states that a reaction temperature increase of 10°C doubles the rate of reaction within a lead-acid system. A mathematical algorithm based on this derivation can be incorporated into the DMT to compensate the measurement of the charging current. The DMT samples the ambient temperature and adjusts the measurement by a factor representing the thermal properties of a battery cell. This modified ambient temperature can be used in a DMT to factor temperature out of a charging current measurement. This compensated measurement allows the alarm provisioner to tighten the alarm thresholds around the nominal charge current measurement. This translates to earlier alarms before a condition becomes a problem.

A battery has temperature limits where other failure mechanisms take place. A compensation algorithm clamps within these temperature limits. Outside this range, a different alarm alerts to extreme temperature.

Dynamic Voltage Cancellation

Designers currently incorporate control circuits such as equalize, sleep and feedback loops, into their constant voltage chargers. A mathematical algorithm can be incorporated into the DMT that adjusts the charging current measurement by a factor based on a measured voltage. This equivalent charging current value allows the alarm provisioning person to tighten the alarm thresholds around the nominal charge-current measurement. This translates to earlier alarms before a condition becomes a problem.

A battery has charge voltage limits where other failure mechanisms take place. A compensation algorithm clamps within these voltage limits. Outside this range, a different alarm alerts to extreme voltage potentials across a battery cell.

COST BENEFIT STUDY OF MONITORING THE FLOAT CHARGING CURRENT

Today, service providers deploy more batteries in outside plant applications. These battery cells are smaller and less costly than the batteries typically used in inside plant applications. Typically, to realize the cost criteria, these batteries inherently have less of a safety factor designed into them by the manufacturer. A monitoring solution has to provide benefits at a cost that the market is willing to endure. Implementing a probe based on the DMT to measure the float charging current meets the demands of these outside plant applications. The float charging current measurement inherently has a higher signal to noise ratio compared to other battery parameters. A DMT-based probe is more inexpensive, reliable, robust, accurate and consistent than any other method to measure the float charging current. Clever algorithms to simplify battery monitoring to a simple event can be incorporated into a DMT. The benefit of a DMT-based probe is high.

Service providers only justify the cost of a monitoring device when compared to the cost of the components it protects. Although a catastrophic event damages many parts of a system, service providers typically make the component comparison with a small percentage cost of the battery. Because catastrophic events, in a service providers' mind, are statistically infrequent, their line of thinking is justified.

Acquisition cost and operating cost composes the total cost of any monitoring device. As demonstrated by this paper, the acquisition and operating cost are small in a DMT-based probe. The cost to implement a DMT-based probe can be under a small percentage of the cost of a battery implemented in a typical outside plant application. With its low cost and high benefit, a DMT-based probe is a viable alternative in battery monitoring.

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