CALCULATED VS. ACTUAL SHORT CIRCUIT CURRENTS FOR VRLA BATTERIES

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INTRODUCTION

A "shorted" lead acid battery has the capability of delivering an extremely high current, 100 to 1000 times the typical discharge current used in most applications. Electrical systems using batteries must be properly protected to avoid potentially dangerous fault conditions. In this paper, we compare the short circuit currents as predicted using generally accepted estimation methods versus actual measured values for individual batteries and battery systems. Practical considerations such as the effects of temperature, state of charge and type of circuit protection device are also presented.

A battery's short circuit current is typically estimated by dividing its open circuit voltage by its internal resistance. While the true DC internal resistance can be determined using a series of discharge tests, it is often simpler to directly measure the battery's impedance or conductance using an AC test signal; several test units are commercially available. Due to differences in resistance versus impedance values, the calculated short circuit currents will naturally be different from those obtained using traditional DC test methods.

OBJECTIVES

In this paper, the following topics regarding short circuit current are presented:
- Comparison of values obtained using estimation methods versus actual measurements for a range of VRLA battery designs
- Comparison of resistance, impedance and conductance measurements as a predictive tool
- Effects of temperature, state of charge and circuit resistance

BATTERY DESIGN

In DC systems, a shorted battery has the potential to deliver an extremely high current in a short amount of time. The magnitude of the current is dependent upon the battery's internal resistance and the external circuit resistance. The battery's internal resistance is related to product design attributes such as plate surface area, inter-plate spacing, separator material type, electrolyte type (gel or absorbed liquid), acid gravity and saturation, connecting strap/weld/terminal post diameters and grid design. For new batteries, both state of charge and temperature can have modifying effects on the internal resistance. As a VRLA battery ages, the resistance often rises due to corrosion of the positive grid, changes in active material structure and electrolyte dry out. The total resistance of the battery string is the sum of the battery internal resistances plus the resistance of external components such as inter-connection hardware and circuit protection devices.

The amount of time to achieve maximum current depends upon such factors as the capacitive and inductive reactance of the battery and the external circuit, as well as the battery's electrochemical response[1]. Often, the peak short circuit current occurs within 5 to 15 milliseconds.

Without some form of protection such as a fuse or breaker, a short circuit condition can cause permanent damage to the battery. In effect the battery can itself becomes the fuse. If the weakest link is within the battery, melting and opening of an internal connection has the potential to ignite the hydrogen/oxygen gas mixture contained within the battery headspace, resulting in a potentially dangerous situation. Melting of the external inter-battery connections may occur, particularly if the terminal connections are loose. While an external failure typically results in a more benign "open" circuit condition, severe and/or prolonged overheating may lead to permanent battery and equipment damage, including the potential for fire.

SHORT CIRCUIT CURRENT ESTIMATION

Using Ohm's law, the potential maximum, zero voltage short circuit current can be calculated by dividing the battery's nominal open circuit voltage by its resistance (I = V/R). By discharge testing over a wide range of currents and measuring the battery's voltage response, its internal resistance can be calculated from the slope of the voltage versus current (R = dV/dI). Extrapolating this line back to zero volts yields the resistance-free or zero voltage short circuit current. As the range and magnitude of discharge currents increase, the accuracy of the resistance and short circuit current values increase.

In IEC896-2 "Stationary Lead-Acid Batteries, Part 2: Valve Regulated Types", the estimated short circuit current is obtained by discharging a battery at 4 times and 20 times its rated 10 hour discharge current (I_{10} at 25°C to 1.75 volts per cell). At the 4X rate, the battery voltage is measured at 20 seconds. After a 5 minute rest without recharge, the battery is discharged at the 20X rate and the voltage is measured after 5 seconds. From these two points, a line is extrapolated back to zero volts to calculate the short circuit current.

A rule of thumb estimation method suggests multiplying the 1 minute rate by 10 to obtain the short circuit current; however, there may be a wide variation between estimated and actual values depending on battery design.

TEST METHOD AND EQUIPMENT

Standard production C&D Dynasty Division VRLA batteries were tested. Products spanned the full range of product sizes, from 33 to 200 AH (20 hour AH capacity), including batteries using gelled and absorbent glass mat (AGM) construction. All the battery models are multi-cell, nominal 12 volt design, with the exception of the 6 volt – 200 AH product. Typically, three samples of each type were tested. Batteries were boosted to full state of charge and allowed to rest for 72 hours before measuring the open circuit voltage (OCV), impedance and conductance. The following commercially available test equipment was used to measure impedance or conductance:

Manufacturer	Model	Type	Frequency
Hewlett Packard	HP4328A	Impedance	1000 Hz
Biddle	Bite	Impedance	60 Hz
Alber	Cellcorder	Resistance	N/A
Midtronics	Micro Celltron	Conductance	unknown

Each battery was constant current discharged at 25°C at 4X its rated AH capacity for 20 seconds with voltage and current readings taken at 0.1 second intervals and at 20X for 5 seconds at 0.05 second intervals, per the IEC standard. The voltage and current was recorded using an Agilent 34970 data-logger. Some batteries were given additional discharges at 100X and 200X for 3 seconds with readings taken at 0.05 second intervals to obtain additional current and voltage points for a trend-line fit and extrapolation to zero volts. After testing, batteries were recharged.

Finally, each battery was "dead shorted", connected to a "shorting circuit" consisting of a shunt (5000A$\pm$ 0.25%), Hall effect transducer [model LEM LT 4000T (4000A$\pm$ 0.5%)], 26 feet of MCM-550 cable and a knife switch. A 2 channel Fluke 190 Scopemeter with automatic triggering was attached to the Hall effect transducer and to the battery terminals. Current and voltage readings were recorded at 0.2 millisecond time intervals from 0 to 0.2 seconds. An Agilent 34970 data-logger was used to monitor the shunt current and battery terminal voltage at 40 millisecond time intervals from 0 to 30 seconds. The "shorting circuit" had a resistance of 1.80 milli-ohms, as measured with a Biddle DLRO micro-ohmmeter. The inductance of the circuit was not measured.

To determine the effect of temperature, sets of UPS12-140 (12V-33AH) batteries were float charged at 13.65V (2.275 volts/cell) for 48 hours at 2, 11, 24, 33 and 40°C in a temperature-controlled environment. OCV, impedance and conductance readings were measured and each battery was "dead short" tested using the test method described above.

To measure the effect of state of charge (SOC%), similar "dead short" tests were conducted on a set of nine UPS12-170 batteries (12V-50AH). Individual batteries were constant current discharged at the 5 hour rate (8.66A) for 0, 1.25, 2.50 and 3.75 hours at 25°C to achieve respective SOC values of 100, 78, 57 and 35% based on the 20 hour AH capacity.

DISCUSSION

Discharge Voltage versus Time

A typical series of discharge voltage versus time curves are shown in Figure 1. This specific example is for a battery discharged at a constant current rate 4, 20, 100 and 200 times its 10-hour discharge rate from an open circuit condition. Similar results are obtained if the battery discharge starts from float charge. Once a load is applied to the battery, the voltage quickly falls to a steady state level where the voltage slowly decreases with increasing time and depth of discharge. The initial voltage drop primarily consists of two components, a resistive loss (V = IR) and an electrochemical voltage loss, also called polarization. Both terms are dependent upon the load current. Note that for these discharges, the time interval between voltage readings was 50-100 milliseconds.

For comparison, typical voltage and current versus time curves for a battery that was shorted using the "shorting circuit" are displayed in Figure 2. For this test, sample measurements were recorded at 0.2 millisecond intervals in order to capture the rapid change in values. Note that steady state minimum voltage and maximum current conditions were attained within 5 to 10 milliseconds. The time constant for this circuit, the time for current to reach 63% of steady state is approximately 4 milliseconds. With a 1.80 milliohm external resistance, the battery voltage dropped to approximately 3.0 volts. The jagged current line is due to signal noise as opposed to variations in the actual short circuit current. For comparison to the 4X to 200X rates used previously, the short circuit current of 1745A at 10 milliseconds in this example is approximately 640 times the 10 hour discharge rate (2.73A at the 10 hour rate).

Figure 1
Voltage versus Time for Range of Discharge Currents

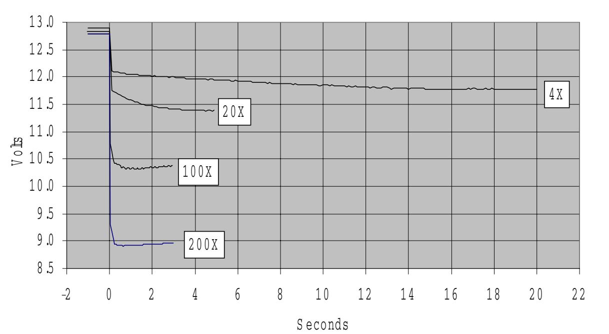
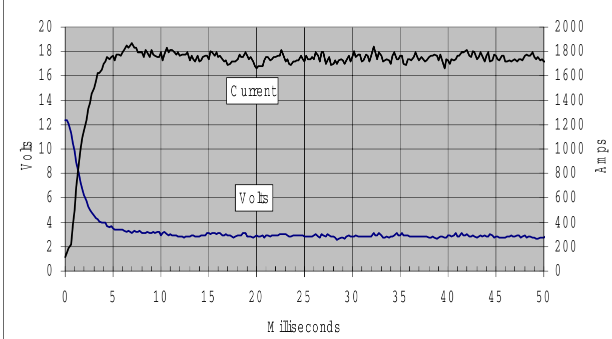


Figure 2
Dead Short Voltage and Current vs. Time



Short Circuit Estimation Methods

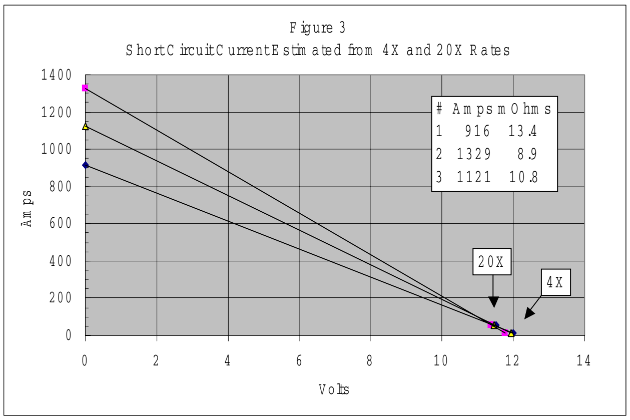
The IEC method of estimating the short circuit current is based on discharging the battery at 4x its rated 10 hour discharge rate for 20 seconds, rest for 5 minutes, followed by a 20x discharge for 5 seconds. The discharge times are long enough to allow the voltages to reach a steady state value (Figure 1). The IEC method specifies to use these two discharge points to draw a line back to zero volts to estimate the short circuit current. The slope of the line is equivalent to the battery's true DC resistance. This method was used to derive the short circuit currents and resistances for three samples (TEL12-30, 12 volt 30AH battery) shown in Figure 3. Because the two voltage and current points are so close together and significantly less than the short circuit value, even small variations in voltage can lead to gross estimation errors. As the test discharge current increases (and load voltage decreases), the estimated resistance and short circuit current values improve. Discharging at 100X and 200X for 3 seconds allows the battery to achieve a steady state voltage (Figure 1). Using the 3 second voltages at the 100 and 200X discharge rates for these same three samples, the predicted short circuit current increases significantly over just the 4 and 20X rates. Using the "shorting circuit", which produces an even higher current and lower voltage, approaching the true zero voltage point, an even better estimate of short circuit current and internal battery resistance will be obtained. The "shorting circuit" test results for the three TEL12-30 samples are shown in Figure 4.

Increasing the range and magnitude of discharge currents (and voltages) significantly helps to improve the accuracy of estimating the battery's short circuit current and internal resistance values. A comparison of the average values obtained using each test method is summarized in Table 1 for the specific battery model (TEL12-30) used in Figures 1 to 4. A comparison of the "zero voltage" short circuit currents predicted by the IEC versus the "shorting circuit" method for the entire C&D Dynasty product line is shown in Figure 5. This graph shows the test values for individual batteries, not averaged results for a given battery model. Typically, three samples of each battery model were tested; the three point data clusters in

Figure 5 are representative of battery and test method consistency. All of the IEC method data points fall considerably below the corresponding values measured using the “shorting circuit”. Underestimating the true short circuit current may result in improper sizing of the circuit protection device.

In this program, all tested products had a 10 hour discharge current that ranged from 2.7 to 18.2 amps. The 4X and 20X rates are relatively common discharge rates and most test laboratories have test equipment to handle this range of currents. However, 100X and 200X rates may be beyond the capabilities of some discharge test equipment, particularly for batteries with large amp-hour capacities.

The “zero voltage” short circuit current is the absolute maximum potential current at theoretically zero resistance. In actual applications, the resistance of the external circuit will reduce the actual short circuit current. With the “shorting circuit”, which had a relatively low external resistance of 1.8 milli-ohms, the short circuit current was significantly reduced from the zero voltage value. In the example with the three TEL12-30 models (Figure 4), the average zero voltage short circuit current was 2320A; however, with the “shorting circuit”, the current was “only” 1700A.



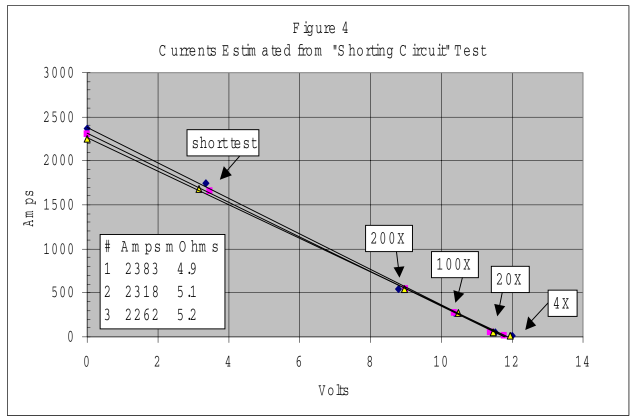
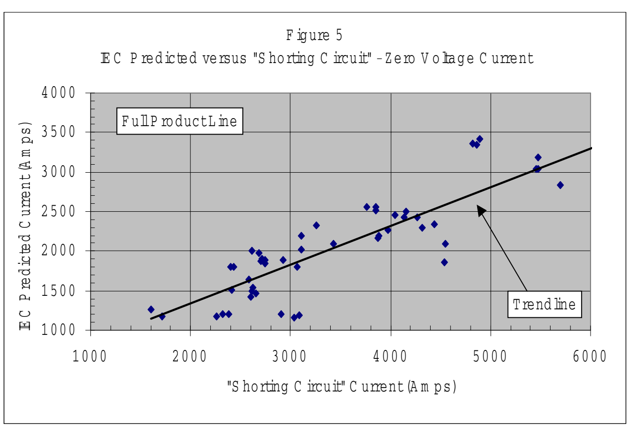
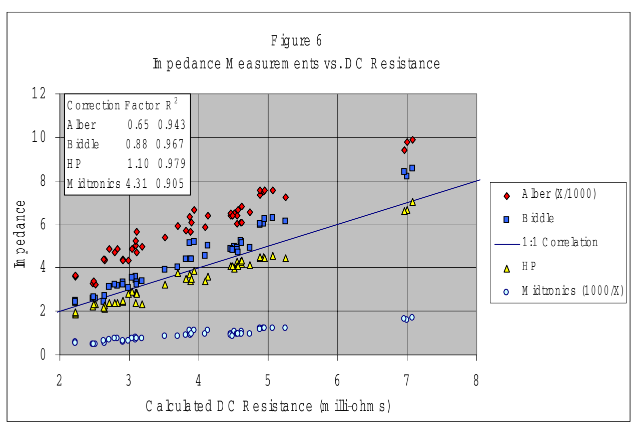


Table 1. Estimated TEL12-30 Short Circuit Current and Internal Resistance by Test Method				
Value	**Units**	**4 - 20X (IEC Method)**	**4, 20, 100, 200X**	**4X-Shorting Circuit**
Current	Amps	1122	2000	2320
Resistance	Milli-ohms	11.0	6.0	5.1





Resistance Measurements

While the short circuit current value at "zero volts" is indicative of the maximum potential current, the internal resistance of the battery is actually a more important value for application purposes where the actual short circuit current may be a significantly smaller value. The short circuit current (I_{SC}) for a battery system can be predicted using Ohm's law, as follows

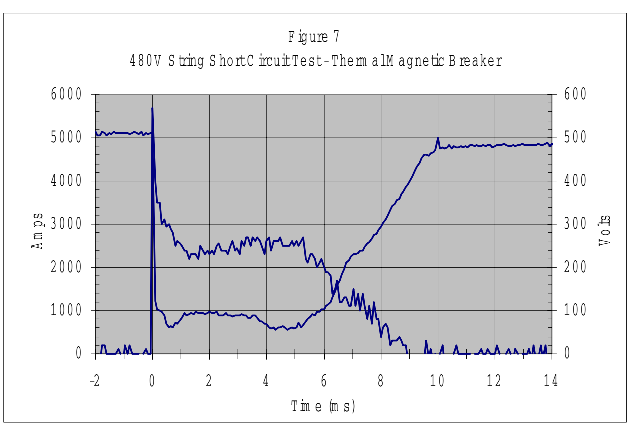
$\mathbf{I_{SC} = V_{BATT} / R_{TOTAL}}$, where $R_{TOTAL} = R_{BATT} + R_{EXTERNAL}$

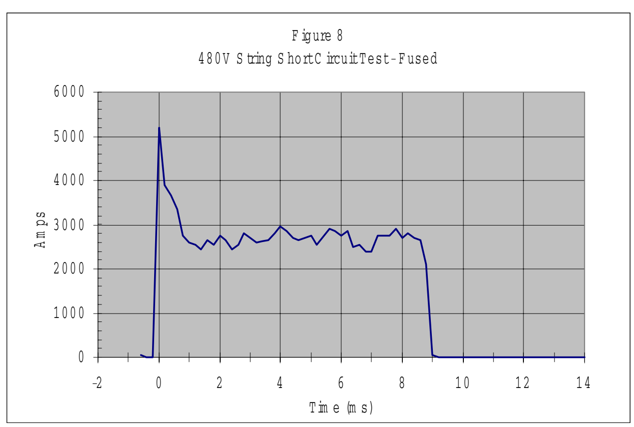
V_{BATT} = Nominal battery system voltage, 2.0 volts per cell x number of cells in series string
R_{BATT} = Internal battery resistance, nominal resistance per battery x number of batteries in series string
$R_{EXTERNAL}$ = External system resistance, including all cables, circuit breaker/fuse and fault

From short circuit tests, the internal battery resistance can be calculated from the slope of the load voltage vs. current line, as demonstrated in Figures 3 and 4. Prior to its final "shorting circuit" test, the impedance (or conductance) of each battery was measured. A plot of the "true" DC resistance (milli-ohms) as calculated from the "shorting circuit" test versus impedance and conductance is shown in Figure 6 for all 12 volt battery models. The Alber resistance values were divided by 1000 to obtain proper scaling. The Midtronics unit measures battery conductance. For graphical and scaling purposes, the Midtronics values shown in Figure 6 are expressed as 1000 divided by the measured value. All of the direct reading values correlate with the calculated DC resistance, following a similar trend; however, there is a wide range in offsets between the various manufacturers' test equipment and the absolute DC resistance. In order to provide a better correlation between each manufacturer's test unit and DC resistance, a correction factor has been calculated to "fit" the test data to the 1:1 correlation line. The multiplication correction factor and correlation coefficient (R^2) is shown in the key on Figure 6. The test technique, including AC frequency portion of the test signal may account for the differences in offset. Although there was a good correlation with 12V batteries, direct reading values for the 6 volt battery model (UPS6-620) did not correlate well with calculated DC resistance for any test equipment with the exception of the Hewlett Packard unit.

480V String Application Tests

A 480 volt string consisting of 40 UPS12-200 batteries was assembled for short circuit testing in a typical UPS style cabinet system with a thermal magnetic breaker (ABB 100A, 3 pole, model S3N100TW). Similar equipment to the prior "shorting circuit" tests was used with the exception that the knife switch was replaced with a pressurized bolt switch to minimize arcing. Data was collected at 0.1 millisecond intervals. Resistance measurements of the interconnect hardware, breaker and external test equipment were measured using a Biddle micro-ohmmeter. Using the equation above, we predicted a short circuit current of 2550 amps [480V / (0.160 + 0.028)], which compares reasonably with the actual measured average steady state test result of 2530 amps during the first 5 milliseconds where the current level was relatively stable. During the first millisecond, the current spiked nearly instantaneously to 5000A, then rapidly dropped to the steady state value. These results are unlike similar tests with single 12 volt batteries using the "shorting circuit" (Figure 2), where the current increased to a steady state value over the initial 4 milliseconds. The differences may be due to the relative length of cabling for each "system" and their inductive properties. Note that the actual string voltage does not drop to zero volts but rather from 510 down to 90 volts due to the circuit resistance. Between 5 and 9 milliseconds the thermal magnetic breaker started to open, resulting in a steady decline in current, not an abrupt current drop. By 9 milliseconds, the current was down to zero. The current and voltage vs. time plots are shown in Figure 7. This test was repeated three times, with ~30 minutes rest time in between each short test, without recharge; the thermal magnetic breaker functioned properly and in a very consistent manner, producing nearly identical voltage and current versus time traces. The batteries were protected by the thermal breaker and remained fully functional.

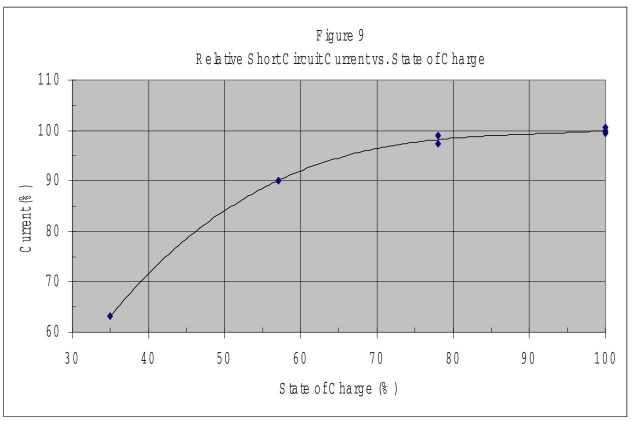


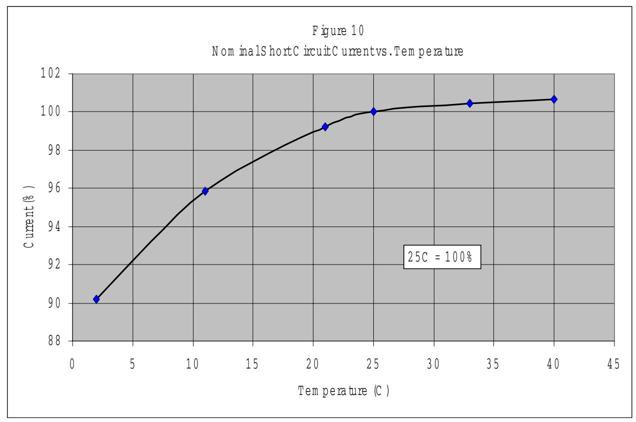


For comparison, the same 480V string was set up with using a fuse (Ferraz A070F400, 700V, 400A semi-conductor fuse) rather than a thermal breaker. Data was collected at 0.2 millisecond intervals. Similar to the prior test, the initial current instantly spiked to 5000A and decreased to a relatively steady state value after approximately 1 millisecond. Unlike the thermal magnetic breaker tests, there was a step change in current and voltage when the fault was cleared; however, the entire event lasted ~9 milliseconds. See Figure 8 for the current versus time plot. Using the equation above, we predicted a short circuit current of 2620 amps [480V / (0.160 + 0.023)] versus the actual steady state average of 2680 amps. The batteries were protected by the fuse and remained fully functional.

State of Charge

In most applications, the battery is on constant trickle or float to keep it at 100% state of charge. However, the potential exists for a short circuit condition to occur after the batteries have been discharged, perhaps at initial installation before the batteries have received a freshening charge. To determine the effect of state of charge on short circuit current, a set of nine UPS12-170 batteries (12V-50AH) were discharged to different states of charge prior to a "dead short" test. Absolute current values were normalized in Figure 9 to show relative decrease in short circuit potential correlating with state of charge. The short circuit current stays relatively high even for low states of charge; for example, currents exceeded 90% of nominal even at ~60% state of charge. Although there is a reduction in positive (PbO_2) and negative (Pb) active material with discharge, there remains ample material for a short duration, high rate discharge. Following the discharge, the rest time before the "dead short" test will also allowed higher gravity acid to diffuse from the separator into the pores of the plates, somewhat replenishing the battery's capacity.





Temperature Effects

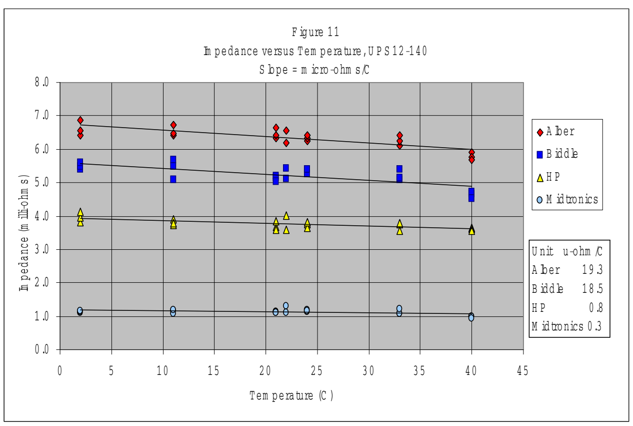
In many applications, the ambient temperature is not a perfectly controlled at 25°C. Sets of three UPS12-140 (12V-33AH) were placed on float at 2.275 volts/cell at each test temperature point for 48 hours for conditioning. Prior to conducting the "dead short" test on each battery, the impedance and conductance were measured. Current values for each temperature were averaged and then normalized based on 100% capacity at 25°C to obtain the results shown in Figure 10. Over the range from 2 to 25°C, the nominal current only changes ~10%, with virtually no change as the temperature increases from 25°C up to 40°C. Acid conductivity versus temperature follows a similar trend; however, conductivity values nearly halve as the temperature decreases from 40 to 2°C. In an equivalent circuit model of a battery, the terminals, straps, plates, separator and electrolyte all act as resistors in series. Estimates of the contribution of each component indicate the acid may account for ~15% of the total resistance of a typical VRLA battery at 25°C. At low temperatures, the decrease in acid conductivity and chemical reaction rates accounts for the reduction in short circuit current.

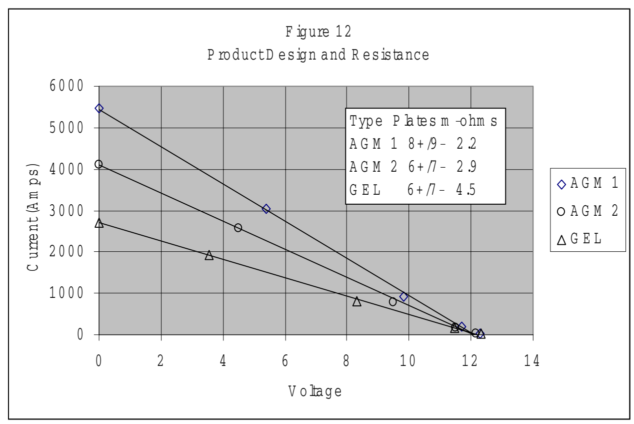
Resistance versus Temperature

As part of the short circuit temperature testing, impedance and conductance readings were measured at each test temperature immediately before the "dead short" test. The relationship between impedance and temperature for each type of test equipment is shown in Figure 11. A least squares trend-line was fit through each set of data points to calculate a value of micro-ohms per degree Celcius from the slope of the line. For scaling purposes, the Alber resistance values were divided by 1000; the Midtronics values were converted from conductance to resistance by taking the inverse and multiplying by 1000. For this temperature range, the slopes are fairly linear. Although there is only a slight decrease in impedance versus temperature, the Alber and Biddle units show a much stronger relationship with a negative slope of 19 u-ohms/C versus only 0.3 to 0.8 u-ohms/C for the Midtronics and HP units. The difference between the test unit's measurement techniques and AC frequencies may be responsible.

Resistance and Product Design
Battery design can have a significant effect on its resistance and short circuit current. Plate count and the type of electrolyte retention (gelled or AGM construction) are two primary contributors to battery resistance. The multiplied product of plate height, plate width and positive plate count yield the opposed positive surface area per cell. Similar to resistors in parallel, as the plate count and corresponding surface area increase, the resistance decreases. Grid design attributes such as frame and wire cross sectional area, grid conductivity and wire pattern (radial, rectilinear) all have modifying effects as well. The type of separator and electrolyte (polyethylene/gel or absorbent glass mat/liquid) also play a major role in product resistance.

A comparison of current versus load voltage and corresponding short circuit currents and resistances for three products that use the same case size and have the plate height and width, but have differing plate counts and separator systems is shown in Figure 12. The UPS12-370 (AGM 1) is designed for UPS high rate discharge applications, with 100AH capacity at the 20 hour rate. This product has a high plate count, 8 positives/9 negatives per cell and AGM construction, responsible for its low resistance and very high zero voltage short circuit current (2.2 milliohms, 5450A). By comparison, the TEL12-90 is also AGM construction, but with only 6 positives and 7 negatives per cell, designed for lower, telecom discharge rates, it still has a 20 hour rating of 100AH. With the reduced plate count and increased inter-plate spacing, resistance increased and short circuit current decreased substantially (2.9 milliohms, 4100A). Finally, the BBG180 is a gelled product with the same plate count and surface area as the TEL12-90. The polyethylene separator and the gelled acid itself account for the significant change in resistance and short circuit current (4.5 milliohms, 2700A). Although all three batteries have the same external dimensions and similar sized plates, and the AGM products have the same 20 hour AH capacity, the products' resistance and short circuit values can vary significantly due to internal design differences.





CONCLUSIONS

Accurate battery system short circuit current and resistance values are required to properly size and select the proper circuit protection device. Estimated short circuit values can vary widely depending upon the test method and measurement technique. Multi-stepped discharge test methods that use a large span in current and voltage provide the best accuracy in estimating battery short circuit current and resistance. Equipment that directly measures a battery's resistive properties can provide a reasonable alternative to discharge tests, with the use of correction factors. Battery system circuit resistance, state of charge and temperature can reduce the nominal zero-voltage short circuit currents. Potentially dangerous short circuit conditions can be prevented with a better understanding of battery and circuit protection operation.

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References
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