A PROPOSED FLOAT CURRENT ESTIMATION TECHNIQUE AND THERMAL RUNAWAY ALARM LIMITS FOR VRLA BATTERIES

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ABSTRACT

A survey of VRLA users and manufacturers presented at Battcon 2001 revealed some interesting statistics. Of the six different monitoring regimes surveyed, all monitored voltage, but only two monitored current. However, the two regimes using current represented 55% of the installations covered in the survey. Temperature was monitored by three regimes, representing only 29% of the installations. The other parameter, ohmic measurements, was monitored at 62% of the installations. Each of these parameters provides useful information in assessing the health of VRLA batteries, however more information is available for some parameters than for others.

For some years now, useful operating limits have been established for voltage and temperature. More recently, useful limits have been developed for internal ohmic measurements. Some work has been done on float current limits, but we believe there is more that needs to be done. Some users are not aware of the normal values of float current expected should they choose to monitor this parameter. In addition, more information is needed with regard to the alarm limits to be used for indicating a potential thermal runaway condition. This paper provides this information as well as the technical basis for it.

INTRODUCTION

Through the years there have been pioneers who have developed instruments for gathering data on various battery system parameters. After introducing a new instrument, there is a need for a trial period to prove its effectiveness. This is not a legal trial, therefore more than testimonials are needed. The cry is for "DATA, DATA, and MORE DATA." Then the data must be analyzed, categorized, and the results publicized before the instrument is recognized. Only then will the instrument be utilized by the industry. I believe many of you will agree with this process, at least in principle.

During this process a normal range for the parameter(s) of interest is proposed and then adjusted as required to improve correlation with the data gathered. The parameter of interest for this paper is battery float charging current. The discussion that follows is arranged to expedite the presentation of the pertinent information. The first section reviews some VRLA battery characteristics that are pertinent to the discussion that follows. The second section presents a float charging current estimation technique for VRLA batteries that can be used should the actual vendor data not be available. The third section presents some proposed thermal runaway alarm limits. These alarm limits were originally developed for Multitel's Float Charging Current Probe (FCCP) instrument, but could be applied to other instruments. The final section presents the technical basis for the earlier sections, should the reader be interested in pursuing this subject. And now, let's get to the discussion!

REVIEW OF VRLA BATTERY CHARACTERISTICS

To achieve the expected life of any battery it must be properly charged and maintained. For the VRLA battery, thermal management is very important due to the internal heat generated during gas recombination. The critical feature of a VRLA battery is the oxygen recombination cycle employed to minimize water loss. All lead-acid batteries generate a small amount of heat internally during float charge due to current flow through the internal cell resistance. However, in a VRLA battery, this heat is very small in comparison to the heat generated by the exothermic reaction at the negative plate due to oxygen recombination. Therefore, a large portion of the float current in a VRLA battery is used to supply this recombination reaction. In addition, higher float voltages and ambient temperatures drive the float current upward and add to the internal heat generated. Once the maximum recombination capability of the battery is reached, the gas vent rate approaches that of a conventional vented lead-acid battery. This venting results in dry-out of the electrolyte; hence more void spaces for passage of oxygen. This in turn increases the recombination reaction and drives the heat even further upward. Ultimately, this internal heat must be dissipated to the environment at a rate sufficient to maintain an acceptable internal cell temperature or thermal runaway will occur.

These VRLA battery characteristics must be considered when selecting the proper alarm limits for a particular battery system. It is important to consider all elements of the battery system, when selecting the normal operating limits and the level of maintenance required. Knowing the normal float charging current and the thermal runaway current limit can help in this process.

ESTIMATING THE NORMAL FLOAT CHARGING CURRENT

The term float charging current is defined as the dc current flowing in the "charging" direction, into a battery, when the battery, charger, and load are connected in parallel. Float charging current may also be called "current acceptance" or "current demand" by some authors. The float charging current flowing into a battery string is dependent upon basic cell electrochemistry, the applied charging voltage, the average internal cell temperature, and the string average state-of-charge. For example, if the battery is partially discharged, the current drawn for at least a short period of time will be much larger than when the battery is fully charged. We will refer to the "normal" float charging current as the expected current flowing into a fully-charged battery, under a given applied charging voltage and at a given average cell temperature.

Since the cells are electrically connected in series, the current flow is the same through each cell in the string although the cell voltages and temperatures may be different. The battery float charging current reflects the average condition of all the cells in the string. When a battery string is initially connected for service, it may be several weeks before the float charging current and cell voltages fully stabilize as a string. One reason for this is some cells are more saturated than others due to manufacturing tolerances, etc. The more fully saturated cells will initially perform more like flooded cells than VRLA cells. Therefore, their current demand may be smaller than the less saturated cells and depending upon the mixture within the string, the battery may perform more like a flooded battery initially. After some time the more saturated cells should dry out somewhat and begin to perform as VRLA cells, with a resulting increase in float current into the more normal range.

Some battery manufacturers provide the normal float current expected under specified conditions. For other manufacturers, it is recommended that you request this information. However, for those users where this information is not available, the following estimate should be sufficient to give an idea of what current level to expect in normal service. A bipolar variation about the estimate is given to accommodate manufacturing tolerances and less than optimum preconditioning during installation. There are various "nominal" rating systems used, but for our purposes, the 8-hour ampere-hour (Ah) rating to an average end voltage of 1.75 volts per cell at 25 degrees Celsius is used as standard. There is usually sufficient information available to convert to another standard if needed.

The following estimates are applicable to most VRLA batteries using lead-calcium (low antimony) pasted plates with an electrolyte specific gravity in the range of 1.25 to 1.300. An average float voltage of 2.30 volts per cell (vpc) is assumed.

For Absorbed Glass Mat (AGM) types:

Float charging current in milliamperes (mA) per Ah_8 = 1.6 +/- 33% or a range of 1.07 to 2.13

For Gelled Electrolyte (Gel) types:

Float charging current in milliamperes (mA) per Ah_8 = 0.8 +/- 33% or a range of 0.54 to 1.06

Remember, the estimates above are based on the 8-hour rating to an average end voltage of 1.75 vpc at 25°C and an average float voltage of 2.30 vpc. If other ratings are used, the estimate must be converted accordingly. Since variations in float voltage and temperature are common, estimates for the more common values are provided below. Tables for AGM and Gel type batteries are provided below for use in estimating float currents at various float voltages and temperatures. The higher values of average float vpc are included for estimating purposes only, for example when charger is set higher for recharge. (The tables assume a doubling of float current for every 10°C increase in temperature or for an increase in float voltage of 0.05vpc average.) The manufacturer's recommended float voltage range should always be followed.

The technical basis for these estimating factors is provided in a later section of this paper.

Table 1 – Estimated Float Charging Current (mA/Ah) for AGM-type, VRLA Batteries

Average Float vpc	Average Temperature of Cells in Degrees C (Deg. F)					
	10 (50)	15 (59)	20 (68)	25 (77)	30 (86)	35 (95)
2.35	1.1	1.6	2.3	3.2	4.5	6.4
2.34	1.0	1.4	2.0	2.8	3.9	5.6
2.33	0.9	1.2	1.7	2.4	3.4	4.9
2.32	0.7	1.1	1.5	2.1	3.0	4.2
2.31	0.6	0.9	1.3	1.8	2.6	3.7
2.30	0.6	0.8	1.1	1.6	2.3	3.2
2.29	0.5	0.7	1.0	1.4	2.0	2.8
2.28	0.4	0.6	0.9	1.2	1.7	2.4
2.27	0.4	0.5	0.7	1.1	1.5	2.1
2.26	0.3	0.5	0.6	0.9	1.3	1.8
2.25	0.3	0.4	0.6	0.8	1.1	1.6

Note: A tolerance of +/- 33% applies to the value read from the table above.

Table 2 – Estimated Float Charging Current (mA/Ah) for Gel-type, VRLA Batteries

Average Float vpc	Average Temperature of Cells in Degrees C (Deg. F)					
	10 (50)	15 (59)	20 (68)	25 (77)	30 (86)	35 (95)
2.35	0.6	0.8	1.1	1.6	2.3	3.2
2.34	0.5	0.7	1.0	1.4	2.0	2.8
2.33	0.4	0.6	0.9	1.2	1.7	2.4
2.32	0.4	0.5	0.7	1.1	1.5	2.1
2.31	0.3	0.5	0.6	0.9	1.3	1.8
2.30	0.3	0.4	0.6	0.8	1.1	1.6
2.29	0.2	0.3	0.5	0.7	1.0	1.4
2.28	0.2	0.3	0.4	0.6	0.9	1.2
2.27	0.2	0.3	0.4	0.5	0.7	1.1
2.26	0.2	0.2	0.3	0.5	0.6	0.9
2.25	0.1	0.2	0.3	0.4	0.6	0.8

Note: A tolerance of +/- 33% applies to the value read from the table above.

Several examples of using these float current estimates are given below.

Example 1: AGM battery rated 80 Ah at the 8-hour rate to 1.75 vpc average and 25°C

The estimated float current at 2.30 vpc = 1.6mA/Ah x 80Ah = **128 mA.**

The variation would be 128 x 33/100 = 42 mA, resulting in a range of 86 to 170 mA.

Example 2: Gel battery rated 50 Ah at the 8-hour rate to 1.75 vpc average and 25°C

The estimated float current at 2.30 vpc = 0.8mA/Ah x 50Ah = **40 mA.**

The variation would be 40 x 33/100 = 13.2 mA, resulting in a range of 27 to 53 mA.

Example 3: What is the estimated float current at 2.35 vpc and 35°C for battery in Example 1?

Referring to Table 1 above, we find a value of 6.4 mA/Ah at the intersection of the row for 2.35 vpc and the column for 35°C. Therefore, the estimated float current = 6.4 mA/Ah x 80Ah = **512 mA**. The same answer can be calculated by multiplying the answer from Example 1 by 4, since the estimated current doubles for every 0.05 vpc increase in float voltage and also doubles for every 10°C increase in temperature.

Remember, for batteries having other variations with temperature or voltage, the principles described in the technical basis can be used. If more specific information is available from the battery manufacturer, that information should be used.

SELECTING A THERMAL RUNAWAY OR HIGH CURRENT ALARM LIMIT

The dissipation of the additional heat generated by the recombination reaction described above is hampered by the limited amount of electrolyte inside the VRLA battery and the dense installation configurations sometimes used. The demand for higher concentrations of power in applications using VRLA batteries has resulted in cabinets and spaces literally filled with batteries with very little free space between the battery containers. Some of the earlier overcrowded installations with higher ambient temperatures failed catastrophically due to thermal runaway. Much has been learned through these earlier failures, but thermal runaway remains a threat for VRLA battery installations. One lesson learned is that this is a system design issue, not just a battery issue. We must keep this in mind when seeking to select a high current alarm limit for warning of impending thermal runaway. A properly installed VRLA battery with higher than normal float charging current may not be a candidate for thermal runaway. However, this same battery may go into thermal runaway at the same current level, when improperly installed. In other words, a high current alarm alone will not protect for all installation conditions. However, on a properly installed battery, a high current alarm can provide an early warning of thermal runaway.

Certain assumptions form the basis of the application of any float current measuring instrument to a VRLA battery system. It is assumed that the battery designer/manufacturer has considered the various limiting conditions of operation and has provided sufficient instructions to the users for the proper application of the battery. In other words, the instructions contain sufficient guidance on float voltage, temperature, spacing, etc to ensure satisfactory operation and performance throughout the design life of the battery. Users are dependent upon accurate and complete information from the battery and charger manufacturers about proper operating limits for their products. Technical papers and articles can supplement this information.

As a minimum, battery manufacturers provide float voltage and operating temperature limits. In addition, some manufacturers provide a maximum operating temperature and the controlling conditions for this temperature. For example, one instruction manual calls for "a maximum permanent operating temperature of 40°C with assured ventilation (reduced service life)." It also defines the recommended float voltage as 2.25 vpc +/- 1% and a maximum boost voltage of 2.35 vpc. Another manufacturer gives a maximum operating temperature of 60°C, with temperature compensation. These are examples of available battery data.

It is assumed that the maximum allowable float current is the current flowing through the battery at the maximum allowable temperature. This is different from the maximum allowable recharge current in that the recharge current is being used to convert lead sulfate in the battery, not just for oxygen recombination. The maximum current limit of interest here is that associated with a fully charged battery. But how do we determine this current limit? There are actually three different alarm limit multipliers that may be applied, depending upon the types of current measuring instruments and battery chargers being used.

Instrument with Temperature Compensated Alarm Limit Algorithm - As noted above, the applied float voltage has a significant effect upon float charging current. In the range of 2.25 to 2.35 vpc average, an increase of 0.05 vpc results in doubling the float current (See technical basis). When used alone a multiplier of 2.1 times the float current at 25°C and the minimum recommended float voltage is recommended. This thermal runaway alarm limit multiplier should be used when the current measuring instrument includes an algorithm to adjust the alarm limit, such as that contained in the FCCP. This type of compensation is dependent upon the selection of temperature sensor(s) location. It should be acknowledged that the current through the battery isn't changed in this case, since the compensation is done in the instrument. However, this type of compensation can improve the effectiveness of a high current alarm limit, when properly applied.

Instrument not using Algorithm, with Temperature-Compensated Charger - Temperature also has a significant effect upon float charging current. For our purposes, it is assumed the float charging current doubles for each 10°C rise in temperature. The standard temperature is assumed to be 25°C and the maximum allowable temperature is assumed to be 40°C. The principles for addressing other responses and limits can be found in the technical basis section. Using equation (1) in the technical basis, a current limit multiplier of 3 times the float current at 25°C can be calculated. This represents the multiplier to be applied to the float current at 25°C and the recommended float voltage in order to determine the expected current at 40°C based on temperature alone. This multiplier should be used when a temperature-compensated charger automatically adjusts the float voltage for variations in temperature and no temperature compensation algorithm is used in the current measuring instrument. This type of compensation is also dependent upon the location of the temperature sensor(s), but does reduce the battery current at higher temperatures.

Instrument not using Algorithm and No Temperature-Compensated Charger - In this case, a combined current limit multiplier of 6 times the float current at 25°C and the minimum recommended float voltage should be used. The user may need to adjust this multiplier, depending upon the degree of protection desired. If there is some measure of temperature control on the battery room temperature, then a tighter alarm limit may be chosen. However, if there is no room temperature control and higher temperature excursions are normal, then a higher alarm limit should be chosen to prevent nuisance alarms. Some judgment must be exercised in selecting the appropriate high current alarm limit.

In summary, the following thermal runaway alarm limits are recommended.

1. A thermal runaway alarm limit of 2.1 times the float current at 25°C and at the minimum recommended float voltage should be used if appropriate temperature compensation is available in the current measuring instrument.
2. A thermal runaway alarm limit of 3 times the float current at 25°C and at the recommended float voltage should be used when a temperature-compensated charger is used and temperature compensation is not be used in the current measuring instrument.
3. A thermal runaway alarm limit of 6 times the float current at 25°C and at minimum recommended float voltage should be used when a temperature-compensated charger is not used and temperature compensation is not used in the current measuring instrument.

The examples below illustrate the use of these alarm limits.

Example 4 – 12-V, 79 Ah AGM-type Battery, Float Current Instrument with Temperature Compensation

This 12-volt battery is rated 79 Ah @ 8-h rate to 1.75 vpc @ 25°C. The recommended float charging voltage is 13.5 to 13.8 VDC per unit average @ 25°C. The per-cell float voltage range is 2.25 (13.5/6) to 2.30 (13.8/6). Using Table 1, we look up 2.25 vpc in the leftmost column and follow that row over until we intersect the 25°C column. The estimated float charging current read from Table 1 is 0.8 mA per Ah. Multiplying this value by 79 Ah yields 63.2 mA. Similarly, using 2.30 vpc, we read an estimated value of 1.6 mA per Ah for the upper limit of float voltage. Multiplying, we get 126.4 mA (79Ah x 1.6 mA/Ah).

For this case where alarm limit temperature compensation is used, the thermal runaway alarm limit would be 2.1 x 63.2 mA or 133 mA. Now let's see how the temperature compensation works. At 25°C, the alarm limit would remain at 133 mA, which is 5% above the estimated float current of 126.4 mA. At 40°C, the algorithm in the FCCP adjusts the alarm limit using a form of equation 1 given in the technical basis. Therefore, the alarm limit would be adjusted to 2.83 x 133 mA = 376 mA. The estimated float current at 2.30 vpc and 40°C is 126.4 mA x 2.83 = 358 mA, which is below the alarm limit. However, if the float voltage increased to 2.33-vpc with no increase in temperature, the estimated float current is 545 mA. This value is above the alarm limit and the alarm would be activated.

If the temperature increased to 50°C and the float voltage remained at 2.30, the compensated limit would now be 758 mA and the estimated float current is 718 mA, which is below the threshold. With a temperature compensated alarm limit, the temperature may rise to an unacceptable value without an alarm. This is one disadvantage to this type of alarm algorithm. For this reason, the FCCP has a separate temperature alarm output set at 50°C. It should be noted that if the voltage increased by only 0.01 vpc to 2.31 vpc with the temperature at 50°C, the estimated float current is 822 mA, which is above the alarm limit, thus activating the alarm.

Example 5 – 12-V, 79 Ah AGM-type Battery with a Temperature-Compensated Charger and No Instrument Compensation

Using the same data from Example 4, but assume a midrange float voltage of 2.28 vpc at 25°C. Using Table 1, we look up 2.28 vpc in the leftmost column and follow that row over until we intersect the 25°C column. The estimated float charging current read from Table 1 is 1.2 mA per Ah. Multiplying this value by 79 Ah yields an estimated float current of 94.8 mA. In this case the thermal runaway alarm limit would be 3 x 94.8 mA or 284 mA. Now let's see how this compares with estimated float currents at various voltages and temperatures. The estimated float current at 2.28 vpc and 40°C is 94.8 mA x 2.83 = 268 mA, which is below the alarm limit. However, only a slight increase in temperature would result in an alarm condition.

Example 6 – 12-V, 79 Ah AGM-type Battery without Temperature Compensation in Charger or Instrument

Using the same data from Example 4, but assume a minimum recommended float voltage of 2.25 vpc at 25°C. Using Table 1, we look up 2.25 vpc in the leftmost column and follow that row over until we intersect the 25°C column. The estimated float charging current read is 0.8 mA per Ah. Multiplying this value by 79 Ah yields an estimated float current of 63.2 mA. In this case we multiply this value by 6 to get the thermal runaway alarm limit of 379 mA. The estimated float current at 2.30 vpc and 40°C is 358 mA (2 x 2.83 x 63.2), which is below the alarm limit. Increasing the float voltage to 2.31vpc without changing the temperature, the estimated float current is 411 mA, which would trigger the alarm.

Similar techniques can be used to select a low-current threshold limit, but this is beyond the scope of this paper. These limits and their selection and application are available on the Multitel website.

TECHNICAL BASIS FOR FLOAT CHARGING CURRENT ESTIMATES

Some VRLA battery manufacturers have provided float current ranges for various products in their brochures. In addition, several technical papers (Ref. 1 & 2) have provided more general float charging current data, representing a cross-section of the various VRLA batteries available. However, various rating systems were used in the references and conversion to a common system was needed. Reference 1 discusses the variable voltage characteristics of VRLA cells and provides a general float current value of 1 mA/Ah_3 at 20°C and a nominal 2.30 vpc float voltage for the AGM type battery. This value must now be converted to the 8-hour rate at 25°C. The ratio of the 3-hour Ah rating to the 8-hour Ah rating is approximately 0.86. Since the variation in float current with temperature is logarithmic, the following equation will be used.

$$\text{Multiplier} = \text{Antilog}\ ((T_2 - T_1)/\text{delta-T}) \times \log 2) \qquad (1)$$

Where: T_2 = Higher temperature
T_1 = Lower temperature
Delta-T = Temperature variation for which current doubles

It is assumed the current doubles for every 10°C increase in temperature. The multiplier can now be calculated.

$$\text{Multiplier} = \text{Antilog}\ ((25-20)/10) \times \log 2) = 1.414$$

Using this multiplier and the data given above, the AGM float current estimate for the 8-hour rate at 25°C is calculated.

$$mA/Ah_8 = 1 \times 1.414/0.86 = \underline{\mathbf{1.6}}$$

Since several cells are connected in series to make a battery, the float current indicates the average performance of the cells within the battery. In addition, most manufacturing processes are under some type of statistical control, resulting in a bipolar tolerance about the average. Reference 2 contains some general float current data in the form of a range of normal values. The source of this data reveals a float current range of 1 to 2 milliamps per Ampere-hour (mA/Ah) at the 20-hour rate for the AGM type at 25°C and 2.30 vpc. Similarly, the float current range is 0.5 to 1 milliamp per Ah for the Gel type. Converting to Ampere-hours at the 8-hour rate as described above yields a range of 1.07 to 2.13 mA/Ah_8 for the AGM type and 0.54 to 1.06 mA/Ah_8 for the Gel type. Converting to a bipolar variation, we calculate the following.

$$((2.13/1.6) - 1) \times 100 = \underline{\mathbf{+33\%}}$$

$$((1.07/1.6) - 1) \times 100 = \underline{\mathbf{-33\%}}$$

Therefore, the float current estimate for <u>Absorbed Glass Mat (AGM) types is as follows:</u>

Float charging current in milliamperes (mA) per Ah_8 = 1.6 +/- 33% or a range of 1.07 to 2.13

Similarly, using the range for the Gel type battery, we can calculate the float current estimate as follows:

$$\text{Estimate} = (1.06 + 0.54)/2 = \underline{\mathbf{0.8\ mA/Ah_8}}$$

$$+\text{Variation} = ((1.06/0.8) - 1) \times 100 = \underline{\mathbf{+33\%}}$$

$$-\text{Variation} = ((0.54/0.8) - 1) \times 100 = -\underline{\mathbf{33\%}}$$

Therefore, the float current estimate for Gelled <u>(Gel) types is as follows:</u>

Float charging current in milliamperes (mA) per Ah_8 = 0.8 +/- 33% or a range of 0.54 to 1.06

These estimates should be applicable to most VRLA batteries using lead-calcium (low antimony) pasted plates with an electrolyte specific gravity in the range of 1.250 to 1.300 and an average float voltage of 2.30 volts per cell (vpc). Comparisons with various generic data as well as specific vendor data were done to confirm these values. Float data from Reference 3 reveals that the float current for a 100Ah VRLA battery was 75 mA at 2.27 vpc and 25°C. Calculating the minimum value at 2.27 vpc for the AGM type yields 74 mA. This reference also confirms a doubling of float current for each 10°C of change in temperature. This current versus temperature information was used in developing the tables of float current estimates.

The variations with respect to voltage shown in the table are based on data from References 1 and 2. These references indicate that in the range of 2.25 to 2.35 vpc, an increase in float voltage of 0.05 vpc (50 millivolts per cell) results in a doubling of float current. If more specific battery data is available, then it should be used for this estimate.

TECHNICAL BASIS FOR THERMAL RUNAWAY OR HIGH CURRENT ALARM LIMIT

The effects of voltage and temperature must also be considered in the selection of a high current alarm limit. The technical basis for the effect of voltage on float current is described in the previous section. For our purposes with respect to the high current multiplier, a slight increase from 2 to 2.1 is used to provide a slight margin above normal operating limits. This multiplier should be used when only the effect of voltage on float current must be considered.

Equation 1 in the previous section provides a means of calculating the effect of temperature upon the float current. Reference 3 provides a recommended high current limit with respect to temperature alone based on certain assumptions. Those assumptions are as follows:

1. The maximum permissible current is the current flowing through the battery at the maximum allowable temperature.
2. The maximum allowable average cell temperature is assumed to be 40°C.
3. The float current doubles for every 8°C increase in temperature.

Using these values in equation 1 from above, we calculate a high current limit multiplier as follows:

$$\text{High Current Limit Multiplier} = \text{Antilog}\ ((40\text{-}25)/8) \times \log 2) = 3.67$$

However, there are some battery systems where the float current doubles for every 10°C increase in temperature. For these systems, a multiplier is calculated as follows:

$$\text{High Current Limit Multiplier} = \text{Antilog}\ ((40\text{-}25)/10) \times \log 2) = 2.83$$

<u>For our purposes, a general temperature only multiplier of 3 is chosen as a compromise</u>. If more specific battery data is available, the selected alarm limit multiplier should be based on that data.

Combining the effects of float voltage and temperature upon float current, a multiplier of 6 times the estimated float current at 25°C and the recommended minimum float voltage is selected.

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