DETERMINING AVAILABILITY OF LEAD-CALCIUM BATTERIES USING CHARGING CURRENT

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Introduction:

Availability, is usually interpreted as the total time a system is capable of performing its intended function divided by the total time the system is required to be operable. This value is usually expressed as a percentage. Applying this definition of availability to batteries we must be able to determine the battery's state of charge and know a battery's capacity (history) to determine whether it is available or not. There are two common methods for assessing the state of charge of a lead-acid battery discussed in the latest IEEE std. 450[1]. The most common method used in the past has been electrolyte specific gravity (S.G.) measurement readings taken with a hydrometer from one or more cells of the battery. The other method to determine the battery's state of charge is the use of a stabilized charging (float) current measured with a sensitive clamp-on ammeter, or a suitable shunt and voltmeter. Both of these methods are correct and commonly used. Recent downsizing and other cost cutting efforts have reduced the manpower available for maintenance and trending have now made the use of specific gravity readings very costly in some cases or impossible to take in others. Some users have turned to automatic monitoring systems with remote reporting capabilities to routinely collect battery data. In addition, many installations have valve-regulated lead-acid (VRLA) batteries which have no provision for measuring specific gravity. With the large numbers of VRLA batteries now in service and being sold today, the use of the float current method of assessing state of charge is expected to increase.

In 1988 we began to measure charging (float) current in addition to S.G. readings. A total of 780 cells were monitored. The results of this experience are summarized in this paper. The analysis of the collected data led us to the conclusion that charging (float) current monitoring is preferred over specific gravity readings for assessing the state of charge of a lead-acid battery.

Another area in which we have found charging current to be of greater use than specific gravity readings is in determining when a battery is ready to be returned to service after a service/performance test. At present, there is no formal procedure for recharging and returning batteries to service. After the test acceptance criteria is satisfied (acceptable discharge), the battery is charged with equalizing charge for a period of time then returned to service following the satisfactory completion of some informal requirements. The time interval between when all the charge has been restored to the battery and when the equalizing charge is complete may be 3 to 5 days or longer. By revising this sequence slightly, several days may be saved in returning the battery to service. By adding a return to service limit using charging current and cell voltage, the equalizing charge can be continued if desired, after the battery has been returned to service to allow time for specific gravity reading to return to normal.

Field data/Experience Summary

In 1988, we began taking battery charging (float) current readings along with the routine specific gravity readings. Shunts were already installed in the circuits such that the current into or out of the battery could be measured. A portable microvoltmeter is used to take the readings. After consulting the battery manufacturers and our A/E in 1988, an initial ceiling values of 1 ampere and 0.5 ampere were established for the larger station batteries and the smaller diesel generator batteries, respectively. These current values were believed to give reasonable assurance that the batteries were fully charged.

Float current readings were added to the weekly surveillance procedures for 9 batteries consisting of a total of 780 cells and a few years later all the other batteries on site were added for a total of 1416 cells. The overall terminal voltage, float current, and corrected specific gravity are summarized in the tables below for batteries SS1B, SS2A, and DG2A. This data is typical for the other batteries. The nominal 8-hour ampere-hour ratings of the batteries were 2400,1650,and 340 (410) for batteries SS1B, SS2A, and DG2A respectively. Batteries SS1B and SS2A each have 120 lead-calcium cells with 1.215 nominal specific gravity electrolyte. Battery DG2A had 60 lead-antimony cells with 1.215 nominal specific gravity until replaced with 410 ampere-hour lead-calcium cells in April 1992.

BATTERY SS1B DATA

	BATTERY VOLTAGE (Volts)	CHARGING CURRENT (Amps)	CORR. SPEC. GRAV.
MINIMUM	132.1	0.12	1.205
MAXIMUM	135.4	0.98	1.233
AVERAGE	134.5	0.65	1.224
STD.DEV.	0.53	0.14	0.005

BATTERY SS2A DATA

	BATTERY VOLTAGE (Volts)	CHARGING CURRENT (Amps)	CORR . SPEC. GRAV
MINIMUM	132.4	0.06	1.198*
MAXIMUM	140.5	2.2*	1.232
AVERAGE	135.1	0.41	.226
STD.DEV.	0.61	0.15	0.005

Note: The values marked with an asterisk (*) are related to a partial discharge of the battery in July 1992 due to a charger failure.

BATTERY DG2A DATA

	BATTERY VOLTAGE (Volts)	CHARGING CURRENT (Amps)	CORR. SPEC. GRAV.
MINIMUM	130.0	0.08	1.206
MAXIMUM	135.6	0.48	1.234
AVERAGE	133.6	0.19	1.218
STD.DEV.	0.92	0.07	0.005

Note: The value marked with an asterisk (*) is due to the change in float voltage made when the lead-antimony cells were replaced with lead-calcium cells in April 1992.

Several observations may be made from an analysis of the detailed data as well as the statistical data tabulated above. The detail data shows very little correlation between the specific gravity readings and the actual state of charge at a given point in time. As defined in IEEE Std 450[1], the battery is considered charged when the float current has stabilized (no significant change for 3 hours) at the float voltage. This was routinely confirmed during each recharge after load discharge testing on many batteries.

As a way of illustrating the charging cycle, let's look at a typical example. Typical data for the recharge following a performance test for a lead-calcium battery is shown in Fig. 1.

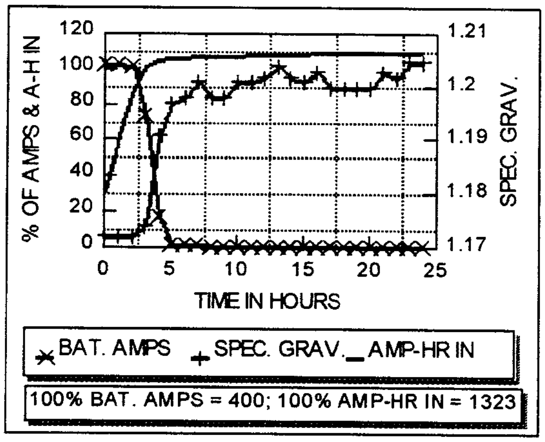

Fig.1 Recharge after Performance Test of Battery SS2A

The high initial current(>400A), limited only by the current limit setting of the charger, flows for about 3 hours. There is then a rapid drop in current followed by a transition into a slowly decaying current. Over 100% of the discharge ampere-hours were returned within 3 hours, but it was not until after 17 hours that the charging current stabilized. Notice that the specific gravity reading is only at 1.205 at 24 hours, 7 hours after the charging current has stabilized. This is still 10 points below the normal, full-charge specific gravity of 1.215.

From the example above, it should be clear that charging current responds more quickly than specific gravity readings to changes in the state-of-charge and provides a better indication of a return to full charge.

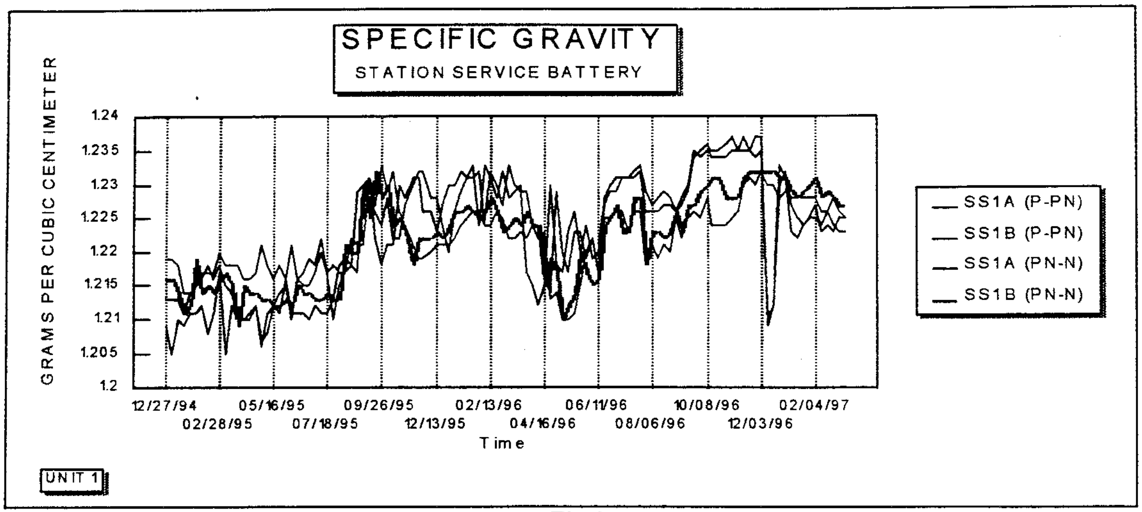

Fig.2

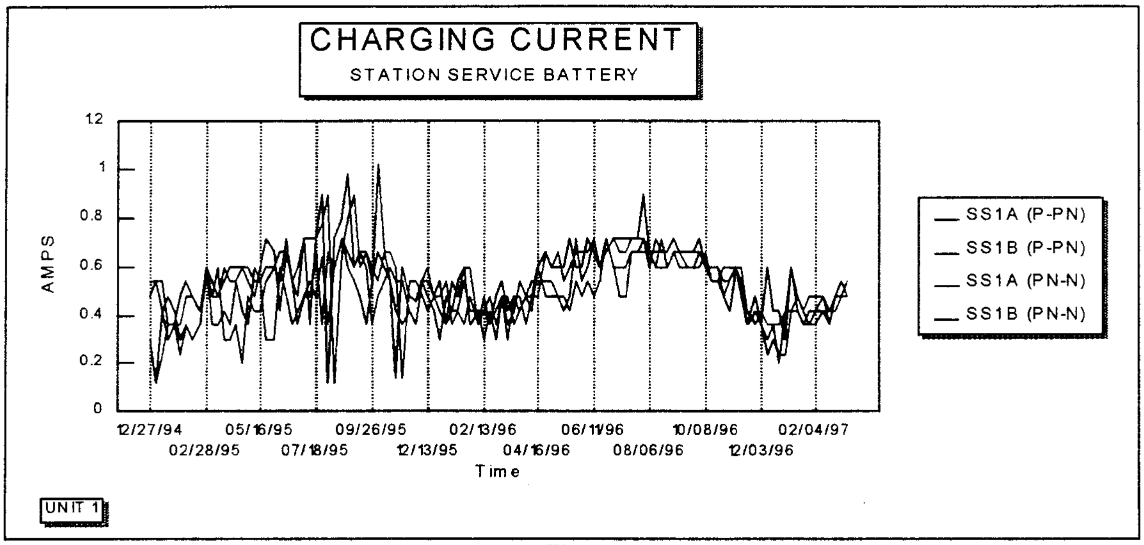

Fig.3

Given only weekly pilot-cell readings (as shown above for spgr. and charging current in Figs 2 & 3) in most cases, with the possibility of daily readings or more often if a battery monitoring systems is installed, a much better assessment of state of charge can be made with charging (float) current than with specific gravity.

In float operation, the battery, charger, and loads are connected in parallel. The charger normally supplies the loads and the float current into the battery. If the charger output is lost or inadequate to supply the loads, the battery immediately supplies the required current. Normal house loads on the diesel generator and station batteries are in the range of 10 to 100 amperes, respectively. Therefore, on a loss of charger output, the battery current immediately changes direction and increases dramatically, at least by a factor of 10. This discharge current would continue until the charger output is restored or the batteries are fully discharged. If the battery has been discharged and then placed on charge, the battery current will initially increase in the charging direction and remain significantly higher (amps vs. milliamps) than normal until the charge has been returned. The relative magnitude and direction of the battery charging (float) current in conjunction with the battery terminal voltage provides a timely, accurate indication of state-of-charge. An excellent gage for use in determining the availability of the battery.

One last observation concerning the float current data should be made. The ceiling value for float current must be selected to allow for the variations expected during normal operation. Since the float current reading will increase dramatically for a partially discharged battery, some cushion above the normal "rated" float current is possible and even desirable. The statistical data shows that the average float current plus 2.5 standard deviations was under the ceiling value on all the batteries. The detailed data from battery SS2A taken during the partial discharge also shows that even for partial discharges, the float current increases dramatically to correctly alert the user to possible problems. Another use of charging current is to use it in determining when a battery is ready to return to service after a discharge test.

Lead-calcium batteries have recharge efficiencies of greater than 95%, so once at least 105% of the ampere-hours removed have been returned, the battery would be in the same condition with respect to capacity as it was prior to the discharge. Assuming the battery capacity was recently verified to be at least 90%, and an aging factor of at least 1.10 was used in sizing the battery, the battery can be returned to service at the time 100% of the ampere-hours discharged have been returned to the battery. If this point in the charge cycle can be determined, the battery could be returned to service at this time with reasonable assurance that the battery would meet its design function if called upon. The remaining charge would be restored while in service and on float charge.

Specific gravity readings have an inherent time lag on charge; which means they will normally be the last parameter to reach the acceptable limits.

The charging characteristics of a typical lead-acid battery using constant potential charging is described below for illustration purposes. Fig. 4 shows a plot of the battery current and ampere-hours versus time for a 2-hour performance discharge test and subsequent recharge on a typical lead-acid battery. The discharge portion is shown as negative and the charge portion is shown as positive in the figure. The battery current is given in percentage of charger output rating and the battery ampere-hours is given in percentage of rated ampere-hours at the given discharge rate used for the performance test.

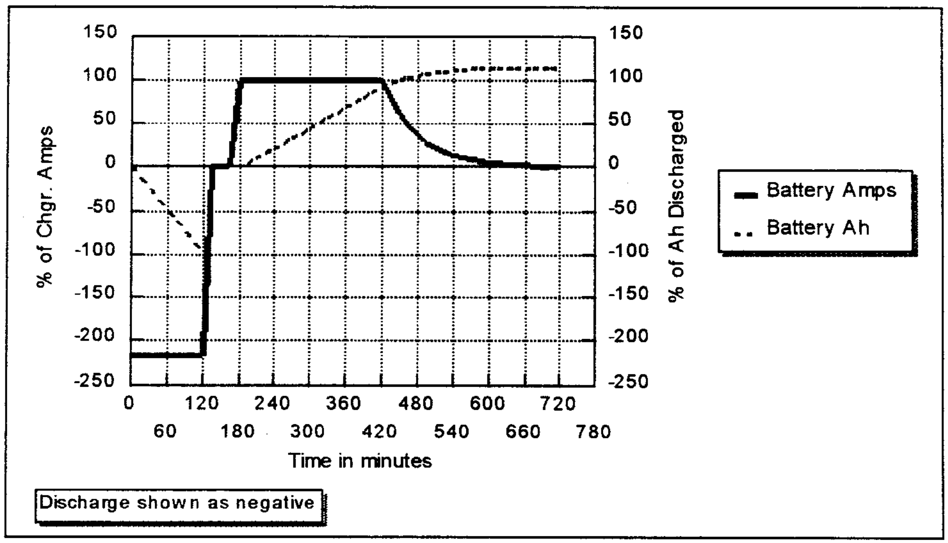

Fig.4

Referring to the figure, the battery is discharged for 120 minutes and at this point in time 100% of the 2-hour rated ampere-hours have been removed. The charger is restored at 180 minutes, referred to as "T_0". The battery current increases quickly to the charger output rating (current limit assumed set at 100% of rating for illustration) and remains there for approximately 4 hours (at 420 minutes in the fig.4). This point in time will be referred to as "T_1 / 0TC" in later discussions and represents the time at which the battery charging current transitions from the current limit rating of the charger to an exponential decay curve.

This exponential decay curve has the mathematical form, shown below.

$$CLe^{(-t\ /\ \mathrm{TC})}$$

where: CL = *current limit rating of charger*
TC = *time constant of exponential function*
t = *time in minutes*

Given the properties of an exponential decay curve, we know that after two time constants (3TC), the value of the function is 4.98% of its maximum value at the start and the area under the curve at this point is over 95.02% of the total area under the curve. This point will be referred to as "T_2" in later discussions. Note that at 5 time constants, the function is essentially at zero.

The area under a continuous function can be calculated by taking the integral of the function and evaluating it between the pertinent limits. With the function in units of current and the abscissa in units of hours, area under the curve represents the charge in ampere-hours returned to the battery. If the current during the period is constant, the integral simplifies to the product of the current and time. We can develop the expression for the ampere-hours returned during charge as follows:

$$AhC = \int_{T0}^{T1} CL\,dt + \int_{T1}^{T2} CLe^{(-t\ /\ TC)}\,dt$$

where AhC = *Ampere-hours charged*
CL = *Current limit rating of charger*
TC = *Time Constant in minutes*
t = *time in minutes*

This simplifies as follows: First, the integral of a constant reduces to a product of current and time. Second, using a table of integrals, the second function can be integrated with the following results.

$$AhC = \frac{1}{60} \times \left[CL \times (420 - 180) + CL \times TC \times \left(e^{(-0)} - e^{(-3)}\right) \right]$$

Further simplification yields the following expression.

$$AhC = CL \times [4 + (0.9502 \times TC\ /\ 60)]$$

Assuming the time constant, *TC*, is equal to 60 minutes, results in the following:

$$AhC = CL \times (4 + 0.95025) = \underline{4.9502\ CL \approx 5CL}$$

The ampere-hours discharged, *AhD*, can be calculated from the data from Figure. The discharge current was 2.17 times the charger output rating (650/300). The current limit, *CL*, is assumed to be equal to the charger output rating for this case.

$$AhD = 2.17 \times CL \times 120\ /\ 60 = \underline{4.34\ CL}$$

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When the percentage of ampere-hours charged is equal to the required percentage of ampere-hours discharged, an ampere-hour balance has been achieved and the battery state of charge is considered restored to the same level of charge as before the discharge. The percentage of ampere-hours charged versus ampere-hours discharged is calculated as follows:

$$\%AhC/AhD = 100 \times 5\ CL / 4.34\ CL = \underline{\mathbf{115\%}}$$

This percentage is greater than the 105% value discussed above and therefore is considered adequate to provide reasonable assurance that the battery would be fully capable of performing its design function if called on at this time.

It should be noted that the battery charging current continues to decrease for several hours until it stabilizes at the charging voltage as described in IEEE Standard 450-1995, Annex B. Therefore, the charging current reading should be taken on equalize voltage.

This discussion provides the basis for selecting a return to service (RTS) limit. Using the current limit rating (CL) of the battery charger connected to each battery, we can calculate the RTS limit by taking 5% of the current limit rating. However, for verification purposes it is recommended that an actual ampere-hour balance be completed for each battery when this method is first used.

In the discussion above, it was assumed that the current limit setting for the battery charger was set at 100% of the output rating. Typically the setting is in the 105 to 110% range and may be as high as 125%. However, for conservatism it is assumed that the setting is at 100% for selecting the return to service limits.

There are various impurities such as antimony or copper that can result in higher than normal float currents in their advanced stages of contamination and or aging. Section 14 of the NMAC Stationary Battery Maintenance Guide and Annex E of IEEE Std. 450-1995

REFERENCES:

[1] IEEE Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage batteries for Generating Stations and Substations, IEEE Standard 450, 1987

[2] G. W. Vinal, *Storage Batteries*, Fourth Edition, New York, John Wiley & Sons, 1955.

[3] Floyd Kyle D., Assessment of Lead-Acid Battery State of Charge by Monitoring Float Charging Current, 1994 IEEE INTELEC Conf. Proc. Pp. 602-608

[4] NMAC Stationary Battery Maintenance Guide, EPRI TR-100248