How to Evaluate Time-Adjusted Battery Capacity Results

Volney Naranjo
Senior Applications Engineer
Megger
Dallas, TX

Robert Foster
Applications Engineer
Megger
Dallas, TX

Daniel Carreño
Applications Engineer
Megger
Dallas, TX

Abstract

This paper presents the results, corresponding analysis and observations from six capacity tests performed on the same battery at different constant discharge rates. Particular aspects related to the test parameters and additional measurements during the tests are discussed in order to provide guidance on how to review and analyze capacity test results. This illustrates the factors to consider when reviewing capacity test results and provides the reviewer broad criteria to read and make decisions from the result. Additionally, taking advantage of performing multiple tests on the same battery, the paper discusses the accuracy of the discharge tables by comparing the result of the capacity when using different discharge rates.

Introduction

Battery load testing provides an accurate measurement of a battery capacity, furthermore, it is the only proven method to measure the capacity and determine the state of health of a battery. Running the test requires a balance between resources and time, and involves careful preparation and logistics. IEEE Std. 450, IEEE Std. 1188, IEEE Std.1106 and industry literature explain in detail how to run the test and the pass and fail criteria. Due to the length and nature of the test, a great amount of information is logged while it is running, especially if individual cell voltages are recorded. All of this information can be utilized to perform a detailed analysis and go further than indicating the percentage capacity.

In most electrical tests, it is possible to repeat a test right away to confirm questionable results or to try different conditions to better understand the measurements. In battery load testing it takes a large amount of time and effort to prepare the battery for a retest: recharge or equalize, rescheduling of resources and coordinating actions related to the operation of the power system affected by the battery under test.

This paper presents the results, corresponding analysis and observations from six capacity tests performed on the same battery at different constant discharge rates. Particular aspects related to the test parameters and additional measurements during the tests are discussed in order to provide guidance on how to review and analyze capacity test results. This illustrates the factors to consider when reviewing capacity test results and provides the reviewer broad criteria to read and make decisions from the result. Additionally, taking advantage of performing multiple tests on the same battery, the paper discusses the accuracy of the discharge tables by comparing the result of the capacity when using different discharge rates.

The battery tested is a 24-cell bank, VRLA, 48 V, which is always under floating conditions at 54 V or 2.25 V per cell. It was installed in August 2016, in a room that remains at approximately at 25 °C year round, it does not support a load and is used for training and instrument evaluation purposes, cycled with very low current for short periods.

Analysis of Capacity Testing

The purpose of the capacity, or load bank test is to determine the true capacity of the battery by finding the time that it takes the battery to reach the end of discharge voltage and compare it to the expected time from the battery manufacturer's published ratings. The ratio between the resulting time and the expected time, with a temperature correction, defines the capacity of the battery in percentage. This method is the Time Adjusted capacity test and is the preferred method for tests longer than one hour.

At first, analysis of a capacity test looks rather simple: the percentage capacity result is compared to the replacement criteria from IEEE standards, which is 80% of capacity. The results should be trended over time to detect degradation, defined by a drop of more than 10% from the result of the previous test. If this is the case, or if the battery has reached 85% of expected service life, the capacity test should be performed annually. In addition to the capacity result, depending on test practices and the tools used, there is additional information in a capacity test that can be analyzed in the results to help understand the condition of the battery and determine maintenance actions. The key data that will provide information for a thorough battery condition assessment is:

- Discharge parameters and conditions such as test rate, duration, and temperature compensation.
- Battery terminal and individual cell voltages during float conditions, after turning the charger off, and during the test.

Discharge Parameters and Conditions

Temperature Compensation

Manufacturers provide a reference temperature at which the battery will perform to specification, generally 25°C or 20°C. Temperatures higher than the reference value reduce the life of the battery. During a performance test, higher temperatures will cause an easier and quicker release of energy resulting in an apparent higher capacity value than at reference temperature. The opposite will happen at temperatures below the reference point. For this reason and for proper results evaluation, it is necessary to normalize the result by applying a temperature correction in the calculation of the capacity; the temperature at the start of the test should be used to determine the correction factor and applied to the capacity calculation: $\%C=(Ta/(Ts*KT))*100$. Temperature correction factors are provided in IEEE Std. 450, IEEE Std. 1188 for lead acid and IEEE Std. 1106 for Ni-Cd batteries.

A proper test report should always include the temperature of the battery prior to running the test. The analysis of the result should verify that the test was performed at a temperature within the recommended testing range from the manufacturer, usually from 18°C to 32°C, and that the capacity calculation considers the appropriate correction factor from the manufacturer recommendations or from IEEE standards.

Test Rate and Duration

In addition to some maintenance activities to be performed prior to a capacity test, the selection of the duration/rate of the test is of critical importance for the preparation and logistics related to the testing as well as for the performance of the battery. Maintaining a constant and fixed discharge rate during the test guarantees the accuracy of the result.

A load, or discharge test, aims to measure the stored energy of the battery in order to compare it to the manufacturer specification, therefore, the test needs to be performed as per specific requirements and conditions: at a constant current or power and down to an end voltage. The temperature of the battery prior to running the test should be recorded and used to correct the capacity. This information is provided by manufacturers for each model as performance tables.

The discharge rate may be different for each battery depending on the application, system conditions or restrictions, and the resources available. Therefore, it is important to know what the implications of a determined test duration are.

Ideally, a capacity test should be performed according to purchase specifications or to envelope the duty cycle of the battery. However, this can be an unfeasible approach. Long duration tests may conflict with limitations of the outage period allowed for the substation and the cost of a backup solution. Selecting a short duration represents the need of a load bank with higher current capability, a bigger instrument or a bulky array of small equipment connected in parallel, larger cables, provisions for an appropriate connection to the battery terminals and in some instances arrangements to cool down or maintain the temperature of the battery room. All of this translates into an increased cost to perform the test.

Once a test duration is defined, the performance tables from the manufacturers should be used and strictly followed to be able to obtain accurate capacity results. The accuracy of the test depends on a constant and stable discharge rate, either current or power. Any significant deviation caused from the use of manually adjusted loads needs to be considered during the analysis of the result in order to determine the effect on the test.

The discharge duration also defines the method for the capacity calculation. The time-adjusted method is recommended for tests durations longer than one hour. For durations shorter than one hour, the recommended method is the rate-adjusted method. Both methods can be used for durations of one hour, however the time-adjusted method uses a simpler approach than the rate-adjusted method and it does not consider battery efficiency related to the discharge time, so, in practice, the time-adjusted method might be conservative for one hour durations.

Once a test rate/duration and a calculation method is selected, it should be used for the life of the battery in future tests for comparison and trending purposes.

Battery Terminal and Individual Cell Voltages

Battery Terminal Voltages

The capacity test measures the battery terminal voltage throughout the test and is used to determine when to stop the discharge, based on the minimum cell voltage multiplied by the number of cells. This overall voltage can be measured through the current cables; however, it is preferable to measure the voltage at the terminals of the battery with dedicated sensing leads, especially when high currents or long runs of current cables are used for the discharge to avoid affecting the measured voltage with any voltage drop across the current cables.

It is of value for the analysis to have the measurements of the battery terminal voltage at the different stages before the testing and not only during the discharge, particularly float voltage (FV) and open circuit voltage (OCV). The float voltage will help to determine if the charger is properly set; a charger with a float voltage setting out of the manufacturer specification can lead to battery deterioration. An immediate drop from float voltage to open circuit voltage after turning the charger off could be an indication of a deteriorated battery, however, this could be a normal effect as a result of a deliberate design. A VRLA battery will have higher specific gravity due to dryout and therefore a higher OCV. Any significant change from FV to OCV may indicate a failure mode depending on the direction and type of battery and it should be consulted with the manufacturer to confirm if there is an actual problem.

Individual Cell Voltage (ICV)
Although the main criterion to stop a test is when the battery terminal voltage reaches the end of discharge voltage, which is obtained from the product of the end cell voltage and the number of cells, not all the cells discharge equally and the deeper they discharge, the faster the voltage will drop. In some instances, a large difference in capacity between individual cells can lead to certain cells discharging beyond the individual end of discharge voltage before the overall voltage reaches the end of discharge level.

If the ICV is not monitored continuously or at all, one or more cells could get closer to polarity reversal. In the end, this affects the capacity result and can be misinterpreted or misjudged as a generalized deterioration instead of a problem caused by some cells. Monitoring the ICV gives the opportunity to make a better judgment of a capacity result and determine proper actions as corrective maintenance or replacement of individual cells.

For the individual cell voltages, IEEE standards recommend measuring the float voltage prior to starting the test, along with three more sets of measurements while the load is being applied. One should be at the beginning of the test and one upon completion. One more set of voltages should be measured during the test at some point. For thoroughness and better data for analysis, it is recommended to have a measurement of open circuit voltages (OCV), as well as a continuous measurement of each cell throughout the test.

The float and open circuit measurement can reveal cells with voltages that deviate from the cell average or from the manufacturer's recommended value. The individual cell float and open voltages should be balanced throughout the string. Differences between cells higher than the manufacturer specifications should be investigated, discarding external factors such as cell shorts or ground faults, or internal issues such as plate polarization or sulfation, which in most cases can be corrected with an equalization charge or replacement of the cell.

Continuous monitoring of individual lead-acid cell voltage throughout the test helps in determining if the test should be paused to bypass one or more cells, or continued without interruption. The criterion to bypass a cell is when the voltage approaches polarity reversal (1 V or less) at a time prior to 90% of the expected testing time. When a low percentage capacity is obtained from a battery test or a substantial change from a previous test is determined, it can be due to a generalized deterioration of the battery or due to only a few cells. Monitoring and analyzing individual cell voltages helps to determine which case the battery is experiencing.

Testing Results and Analysis
Capacity Results:
In addition to the acceptance test, five capacity tests were performed on the battery, each test with a different discharge rate: 1, 2, 3, 4, and 8 hours. *Table 1: Battery Overall Results*, shows the date, temperature, correction factor, discharge rate, expected duration, actual test duration, calculated capacity, and overall float, open, start and end voltages.

Test No.	Test Date	T [C]	Correction Factor	Discharge Rate [A]	Expected Duration [h:mm]	Test Duration [h:mm:ss]	Capacity [%]	Float V	Open V	Start V	End V
0	11/16/16	25	1	22	4:00	5:24:14	135.10				
1	3/10/17	26	1.006	63	1:00	1:18:29	130.03	54.55	54.46	50.92	41.98
2	3/14/17	24	0.986	13	8:00	10:31:11	133.36	54.60	54.34	52.55	41.98
3	8/30/17	25	1	22	4:00	5:12:23	130.16	54.14	54.02	52.28	42.75
4	9/6/17	25	1	38	2:00	2:10:54	109.08	54.15	54.08	51.48	43.97
5	9/13/17	25	1	28	3:00	3:00:05	100.05	54.15	54.01	51.95	44.48

Table 1: Battery Overall Results

The battery was installed in August of 2016 and the capacity measured at the commissioning test (Test 0) in November 2016 was 135%, and although the two tests that followed (Test 1 and Test 2) show a decrease in capacity it is not recommended to compare these results because the tests were performed at different discharge rates.

Test 3, performed five months after Tests 1 and 2, almost 10 months after the commissioning test and at the same discharge rate, shows a result around 130%, indicating a decrease in capacity of 5% from the commissioning test.

Despite the fact that Test 4 and 5 were not performed at the same rate as the commissioning test and they are still above 100% capacity, they show a total decrease of 25% and 35% of capacity from the acceptance test after less than a year. From IEEE standards, when the capacity reduces more than 10% from the previous test, which is generally expected to be 5 years in between testing, it is considered a degradation on the battery, and hence, additional information is required to determine the cause of the decreased capacity. Analysis of the individual cell voltages is very helpful for additional assessment.

Individual Cell Voltage (ICV)

Though the initial 5% decrease from the commissioning to Test 3 is not above the criteria recommended by IEEE standards, it is a high decrease in less than one year. The subsequent decreases of 25% and 35% in Test 4 and test 5 from Test 0 are not normal and further analysis is required to determine if it is a generalized battery deterioration or due to just a few cells. This is easily determined by reviewing the behavior of the individual cell voltages throughout each test. The following bar charts (Figure 1 to Figure 5) show the voltage of each cell for Test 1 to Test 5 respectively. The top of each bar (top of blue color) represents the FV, the top of the white area represents the OCV and the top of the green or yellow area represents the end voltage. *Table 2* shows the cells for which the voltage went below 1.75 V during a test, the number of times each cell went below the limit and the amount of cells that went below the limit on each test.

The tests were allowed to run to overall end voltage (42 V) or time completion with cells that went below the established end cell voltage (1.75 V) following IEEE recommendation to continue the test if the test is near 90% to 95% of expected completion.

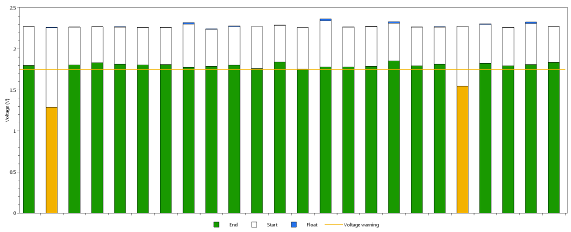

Figure 1: Test 1, Individual Cell Voltages (1-Hr Test)

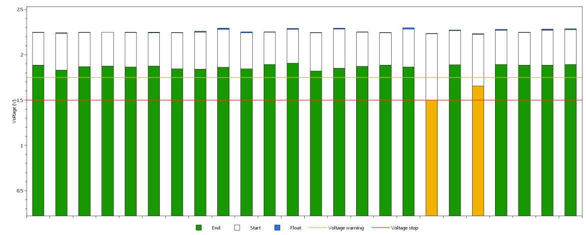

Figure 4: Test 4, Individual Cell Voltages (2-Hr Test)

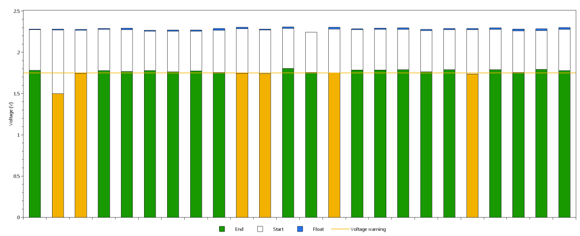

Figure 2: Test 2, Individual Cell Voltages (8-Hr Test)

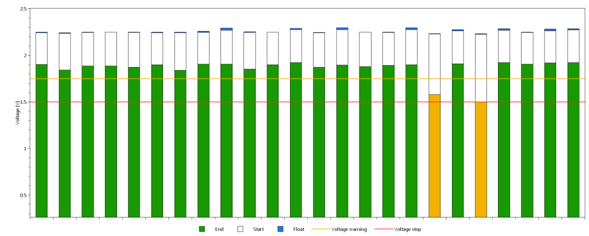

Figure 5: Test 5, Individual Cell Voltages (3-Hr Test)

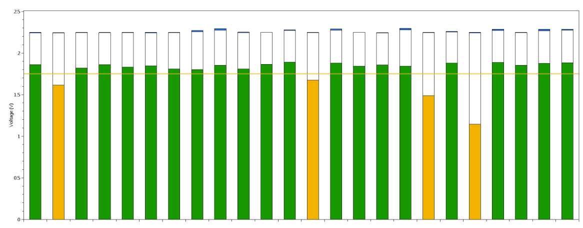

Figure 3: Test 3, Individual Cell Voltages (4-Hr Test)

Battery A, Cells Below 1.75 V									
Test No.	Cell 2	Cell 3	Cell 10	Cell 11	Cell 13	Cell 14	Cell 18	Cell 20	No. of Cells Per Test
1 (1-Hr test)	x							x	2
2 (8-Hr test)	x	x	x	x		x		x	6
3 (4-Hr Test)	x				x		x	x	4
4 (2-Hr Test)							x	x	2
5 (3-Hr Test)							x	x	2
Occurrence	3	1	1	1	1	1	3	5	

Table 2: Summary of cells below 1.75 V

When reviewing ICV results, the ideal expectation is to have a uniform discharge on all of the cells. Test 2, shown in Figure 2, depicts this behavior where all cells, except cell number two, have discharged to approximately the same voltage at the end of the test, indicating healthy cells and a balanced discharge. Therefore, the cells that dropped below 1.75V in this test are not considered to be in poor condition because they did not deviate significantly from 1.75V, with the exception of cell number two.

After analyzing the individual cell voltages on each test and reviewing the summary shown in Table 2, it is possible to conclude that the decrease in capacity observed through the different tests is not a generalized battery deterioration but rather caused by the weakness of individual cells, mostly two at a time.

Out of the weak cells from tests 1, 3, 4, and 5, cell 2 and cell 18 dropped significantly below the end of discharge voltage during three tests, and cell 20 dropped below the minimum voltage in every test. For cell 2, it is important to highlight that the occurrence happened on the first three tests and for the last two it recovered and maintained, performing well all the way through to the end of the tests. One possible explanation is that the cell was not fully developed in the first few tests and needed some cycling for full formation, further testing should be performed at the same duration of tests 1-3 in order to make a more definite conclusion. Lastly, for cells 18 and especially cell 20 it is observed that they failed consistently, these cells should be investigated to determine if they require corrective actions or replacement.

Discharge Tables Accuracy

Due to the inherent internal impedance of a battery, if a current higher than the rated current is demanded from the battery, the losses from the energy dissipation due to the internal ohmic value will be determined by the I^2Z characteristic. This represents a non-linear reduction in the efficiency of the battery performance at higher currents and consequently a reduction in the capacity of the battery when short duration rates are used for testing. Manufacturers account for this in their discharge tables and it is important to be conscious of this when selecting the rate. Once the rate is selected for the first test, the subsequent test should use the same rate.

Figure 6, shows the results from the battery plotted by the selected discharge rate. It can be identified that the results for eight, four and one hour tests reproduce the results very accurately. The two and three hour tests were omitted from the graph since these tests were stopped prematurely to protect the cells and therefore an accurate capacity calculation could not be obtained.

From these results it can be determined, for this particular battery, a wide range of discharge duration can be selected yielding very similar capacities. With that being said, this is not an indication that a different discharge rate can be used each time the test is performed but merely that choosing a discharge rate upon commissioning is not necessarily critical. Once a discharge rate is chosen upon commissioning or first capacity test, the same discharge rate should be used for the life of the battery.

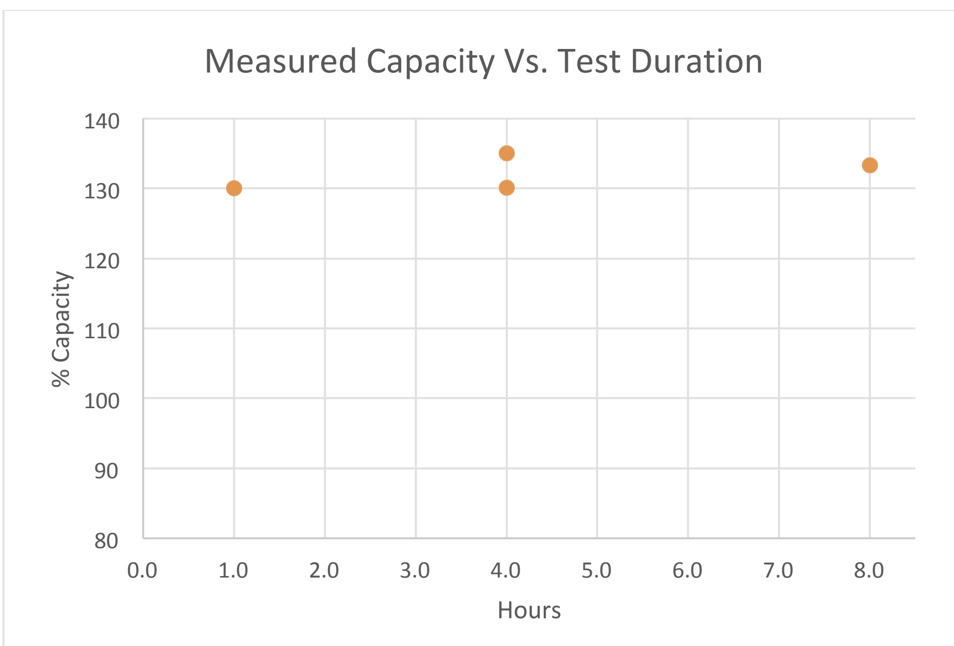

Figure 6: Capacity results by test duration

Conclusions

Before determining a diagnostic from a battery capacity result and judging it only by the percentage, it is important to confirm the average cell temperature at the beginning, and if a correction factor was used or is required, then it needs to be compared to previous results. If a decrease of ten percent or more is observed, it should be investigated to determine the root cause.

Valuable information is obtained from the float and open circuit voltages so these should not be neglected, furthermore, monitoring individual cell voltages throughout the entire test is critical in determining if a reduced capacity is due to a few cells, or to a generalized deterioration of all cells.

The discharge rate to be used for the test has a direct impact on the resources and an appropriate balance between the duration, backup supply and testing equipment is desired to minimize the cost of the test. Understanding and using the discharge tables for each battery is paramount to obtaining accurate results. Selecting the discharge time in the beginning is not necessarily critical as long as manufacturer's specifications are followed, but once a discharge rate is chosen, the same rate should be used for subsequent tests in order to be able to compare results.

References

1. IEEE Std. 450-2010 IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.
2. IEEE Std. 1188-2005 IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications
3. IEEE Std. 1106-2015 IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications
4. ANSI/NETA MTS 2015 Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems