TIME (ONLY) REFERENCED BATTERY RUNDOWN TEST

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Abstract

IEEE Standards 450 & 1188 call for periodic discharge tests to verify a battery can perform as manufactured. Since *off-line* discharge tests of individual strings using load banks are expensive and time-consuming, it is not usually performed in telecom.

In conjunction with ohmic testing, another popular gauge to validate capacity is a test known as the *rundown test.* It is particularly useful in applications with sufficient load as in telecom. Most DC power plant controllers incorporate a feature to automate this test, which amounts to lowering the plant voltage so the battery bank powers the load instead of the chargers. In a typical implementation, the objective is to make sure the battery powers the load for a preset duration before a specified end-voltage occurs.

The test is valuable but crude since it yields a pass/fail outcome and offers no granularity or understanding as to how close the battery is performing in relation to the expected reserve time.

Another drawback is having to engineer the desired test duration and voltage threshold, which will vary according to the bank capacity and expected load. It also requires using battery discharge tables, to approximate these values. The key is to avoid settings that lead to false alarms. Similarly, the test should not lead to a "false positive," the case when a test passes but the battery has reached end-of-life. Further, depending on how the test is used, there may be a maintenance aspect to the test settings if the load current changes significantly.

A simpler, more insightful rundown test could be standardized if there was a gauge that could reliably predict reserve time. Then using the planned end-voltage (e.g. 1.75 vpc), a test could be setup to provide a better understanding of the *predicted* battery reserve time. A separate *test* end-voltage would not be required.

Conventional software-based fuel gauge models that totalize battery current are inherently complex, prone to error and generally suspect. An intriguing option is the voltage-slope fuel gauge described in the US patent 6,211,654. Since it's based on a natural phenomenon, this algorithm could be a useful gauge for baselining and trending capacity. But how well does this algorithm work in the case of an older VRLA battery that has a dry-out condition?

The reader is acquainted with the science behind this fuel gauge algorithm and is then presented data taken during an extended discharge of an older VRLA string. The conclusion should not be surprising, but the data also suggests how this algorithm can be used to flag other capacity issues, akin to a "check-engine" alarm. Even so, the results do suggest that to ensure the reliability of the algorithm, equipment or practices (e.g. impedance testing) must be in place to detect the VRLA battery dry-out condition.

Introduction

In telecom applications a *rundown* test is sometimes used to validate battery capacity. This test is possible in part because of the sizeable load. While the test is valuable, one drawback is the test must be *engineered* for each unique application; a desirable test duration and end-voltage must be determined. In most implementations the test is crude because it only yields a pass/fail outcome and offers no granularity or understanding as to how close the battery is performing in relation to the expected reserve time.

A more insightful and simpler rundown test could be standardized if there was a gauge that predicted reserve *time* in a consistent way, without having to account for varying battery capacity and load in each application. With such a gauge and using the planned end-voltage (e.g. 42V), a test could be set up to provide a better understanding of the *predicted* battery reserve time. A separate *test* end-voltage would not be required.

The reader is first acquainted with the science behind a fuel gauge algorithm based on physics, and then presented data taken during an extended discharge of an old VRLA string with a dry-out condition. The conclusion may not be surprising, but the data also suggests how this algorithm can be used to opportunistically flag other capacity issues, akin to a “check-engine” alarm. Perhaps more importantly, it will become apparent that obtaining the maximum benefit of this fuel gauge, routine battery impedance testing should be performed.

Conventional Rundown Test

The purpose of the rundown test is to validate battery availability and capacity in a controlled manner using the system load. Depicted below, the idea is to mimic an outage by lowering the voltage, so the batteries begin to carry the load. If the batteries do indeed fail, the rectifiers are still online to power the load.

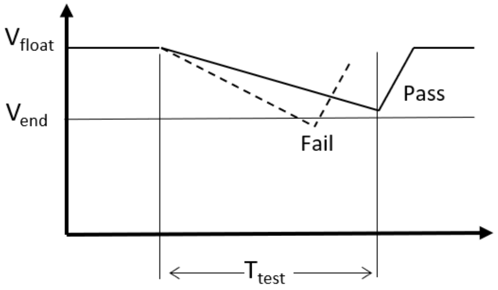

Fig 1. Depiction of Typical Rundown Test

To conduct this test, the desired test duration and voltage threshold must be determined and will vary according to the bank capacity and expected load. It also requires using battery discharge tables (voltage-time profile), to approximate these values. The key is to avoid settings that lead to false alarms, and to avoid settings that lead to “false positives” (i.e. when the test passes but the battery has reached end-of-life).

As mentioned, one drawback of this test is that it yields a pass/fail outcome only, offering no granularity into understanding how close the battery is performing relative to the expected (engineered) reserve time. Another issue is that, depending on how the test is implemented, there may be a maintenance aspect to the test settings if the load current changes significantly. Voltage and/or time settings would have to be recalculated.

While the rundown test is valuable, it could be easier and more intuitive to setup. For example, it would be more natural to specify an expected reserve time (e.g. 8 hours) along with a threshold percentage (e.g. 80%).

Energy Bucket Fuel Gauge

Many conventional battery fuel gauges (as found in a cell phone) treat the battery as a bucket of energy. Charge current and discharge current are totalized and adjusted according to a “charging efficiency factor. ” Fuel gauges like this may also consider temperature, battery age and discharge history to adjust the actual state-of-charge (SOC). More worrisome is that some versions expect the user to update the charging efficiency over time. As with any man-made model, fuel gauge solutions of this type may work in the general case but will fall short in extreme situations, such as when batteries experience premature end-of-life (EOL).

Posing an additional challenge in telecom is the aspect of measuring the current, an entirely different class of problem than measuring current in a cell phone. For one, the difference in the charge and discharge currents can be two orders of magnitude or more, which creates various accuracy issues in the sensing circuits.

Further, not all systems measure battery current directly. Using a shunt or Hall effect sensing device adds cost, and in the case of the shunt it may be considered a single point of failure. In some cases, the battery charge current is grossly approximated by subtracting the load current (measured via a load shunt or hall-effect sensor) from the total rectifier current.

Measuring rectifier current is another challenge. The technique for measuring rectifier current varies between designs and manufacturers. Some designs employ shunts in the output, but this is costly. One design the author encountered used braided litz wire for a shunt! Another design inferred the rectifier current based upon the input power and output voltage as computed by the (digital signal processor) controlling the rectifier. Rectifier current predictions using these techniques vary and may only be 5% accurate.

Predictions from these battery current totalization models may be accurate to within a few percent. Moreover, while models are good for estimating average or typical conditions, they do not account for poor inter-cell connections nor weak cells that essentially hasten the arrival of the end-voltage during the discharge. In general, model-based fuel-gauge prediction schemes are not relied upon.

With so many variables (software models and electronics) and things that can go wrong, it is easy to understand why man-made fuel gauge models instill little confidence as to their accuracy and reliability. Model-based fuel gauges present a host of dependencies and design challenges. Without seeing data, it’s hard to imagine any such model-based gauge being better than 10% accurate across the range of operating conditions.

Voltage-Slope Fuel Gauge

With the assumption that the known VRLA aging dry-out issue is considered, the author submits that the reserve time algorithm described in US patent 6,211,654 is a pragmatic and credible approach to implementing a robust fuel gauge for telecom applications. Part of the algorithm’s appeal is the self-calibration method[1].

Based upon a natural phenomenon and using voltage only, the remaining reserve time can be gauged relatively early into a discharge for flooded and vented lead-acid applications having sufficient load. While the gauge is self-correcting in the presence of weak or dead (shorted) cells adding to its robustness, the caveat related to VRLA dry-out remains. Nevertheless, the voltage-slope fuel gauge algorithm remains useful since it can account for other unexpected situations. For example, when used in conjunction with an 80% capacity threshold one implementation of this gauge detected a string that failed prematurely shortly after its commissioning.

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[1] The patent describes 3 methods, including one that employs a correction factor. The reader is encouraged to review the patent, which also includes test data for a range of batteries. However, the data presented herein is also used to *illustrate* the algorithm accuracy.

The X-Factor Replaces Current

A common hurdle to appreciating the voltage-slope fuel algorithm is the basic idea that current measurement is NOT required to predict the remaining time-to-empty (TTE). To many, this is counter intuitive or just "too good to be true." In a real sense though, the discharge curve is a *signature* of the battery embodying its state-of-charge (SOC), age, discharge history and the state-of-health (SOH).

The algorithm can be understood by looking at figure 2 while considering the following:

1. The slope of the battery voltage (dashed line) steepens with increasing discharge rates (e.g. 4h vs. 6h)
2. During the discharge, the slope *projects* a line that intersects the desired end-voltage (e.g. 1.75 vpc)
3. The *projected* line crosses the end-voltage at a time-multiple (X) of the actual remaining TTE
4. The multiple (X) *varies* according to the desired end-voltage (e.g. for 1.75 vpc, X = 2)

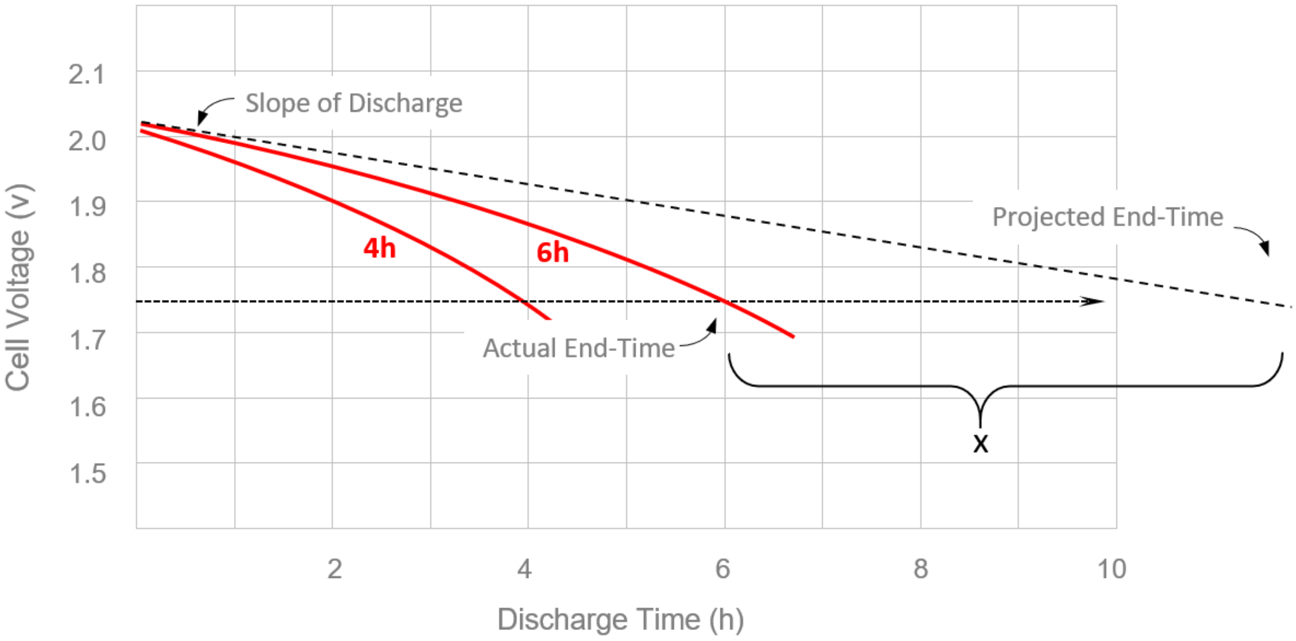

Fig 2. Depiction of Voltage-Slope Relationship

As one might expect, the X-factor varies according to the pre-determined end-voltage. For example, a 1.75 vpc end-voltage requires one X-factor, while a 1.65 vpc requires a different one. These values are listed in the patent.

During a discharge and after the initial coup-de-fouet period, the algorithm can predict the remaining TTE based on the slope. If the battery is fully charged prior to discharge, the TTE value can then be added with the elapsed discharge time to create a useful new metric termed here as *Calculated Reserve Time* (CRT). This metric would correspond to total backup reserve time of the battery plant.

One final remark about the algorithm. The patent also describes a *self-calibration* method whereby a correction factor is determined and used to adjust predictions if the battery is performing better or worse than expected.

Time Referenced Rundown Test

With a basic understanding and a new fuel gauge in place, it is then possible to create another type of rundown test that is more intuitive and time-based. For this new test, one could expect to enter the *engineered* reserve time (e.g. 8 hours) and a percentage threshold (e.g. 80 %). This is more natural and avoids having to use battery discharge tables to engineer and maintain a test voltage-time *pair* for each application.

Like the conventional rundown test, this test would be conducted on a charged battery (e.g. 24 hours on float).

Another benefit of this approach is that it can be used to assess backup reserve opportunistically, whenever an AC outage of sufficient duration occurs. Opportunistic tests should be contingent upon the battery being under float charge for at least 24 hours.

A voltage-slope fuel gauge also makes it possible for the system controller to record statistics on how the battery is performing with respect to the calculated reserve time. For example, it would be easy to record a baseline value at commissioning (e.g. 7.9 hours) and then annually thereafter.

One final remark about the Calculated Reserve Time metric. A downward trend in this metric does not necessarily mean the battery has an issue. A downward trending CRT could also result from an unanticipated increase in load current or poor strap connections, for example.

Fuel Gauge Test on Older VRLA String

Below is the discharge curve for a 25 Ah battery discharged[2] to 42V using a 4A load. This older battery lasted only 3.25 hours (195 min) but note the points where the voltage decreased rapidly, characteristic of cell dry-out and loss of capacity. The first drop could be related to one cell, while the second drop could be multiple cells.

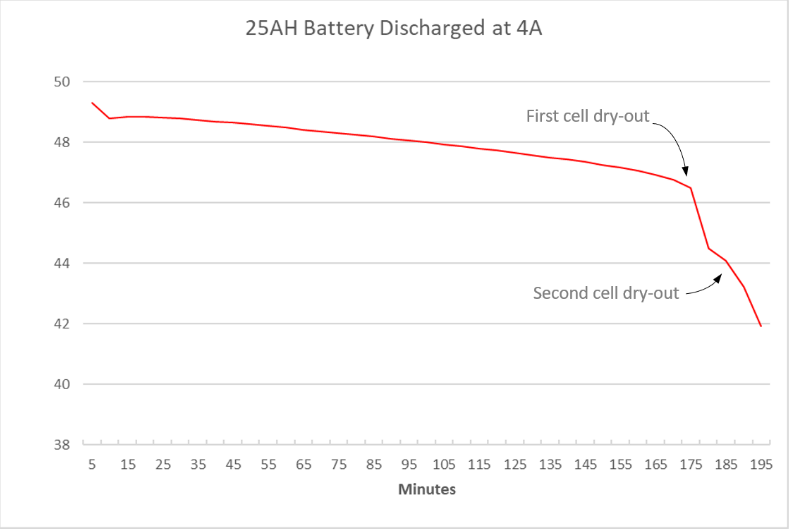

Fig 3. Discharge Curve of 25Ah Battery using 4A Load

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[2] The author wishes to recognize and thank Cliff Murphy and UNIPOWER, LLC for conducting this test.

Test Results

Table 1 below is a portion of the test results for the discharge shown on the previous page. The full test results are shown in Table 3. In addition to discharge time (minutes) and voltage (millivolts), the columns include the delta (mV between readings), time-to-empty (TTE) prediction in minutes, and calculated reserve time (CRT) in hours.

The test results presented here were primarily intended to see how the algorithm works with an older VRLA string having cells with a dry-out condition. However, it can also be shown how the results give credence to the accuracy of the algorithm when a loss of capacity is factored in.

To understand how the algorithm performs with these older VRLA batteries, one first must understand how and when predictions become valid.

Valid predictions only occur after the coup de fouet dip when they are consistent. Here, it took 20 minutes before the slope resumed a downward trajectory and another 35 minutes before readings became consistent.[3]

Min	mV	delta	TTE (min)	CRT (hrs)	Slope	Comments
0	54083					
5	49288	4795	4	0.1	15.9833	
10	48790	498	34	0.7	1.6600	
15	48847	-57	-300	-4.8	-0.1900	
20	48845	2	8556	142.9	0.0067	
25	48819	26	656	11.3	0.0867	
30	48784	35	485	8.6	0.1167	
35	48740	44	383	7.0	0.1467	
40	48692	48	349	6.5	0.1600	
45	48643	49	339	6.4	0.1633	
50	48589	54	305	5.9	0.1800	
55	48535	54	303	6.0	0.1800	<= First valid prediction
60	48480	55	295	5.9	0.1833	
65	48422	58	277	5.7	0.1933	
70	48365	57	279	5.8	0.1900	
75	48305	60	263	5.6	0.2000	
80	48246	59	265	5.7	0.1967	
85	48184	62	249	5.6	0.2067	<= Not normal for CRT to shrink!
90	48122	62	247	5.6	0.2067	

Table 1. Portion of Data for Discharge Curve of 25Ah Battery using 4A Load

In this case, the predictions are consistent and indicate a 6-hour reserve. But in fact, the actual reserve time was only 3.25 hours.

While the voltage-slope algorithm is inherently self-correcting over the discharge, the results here clearly indicate that predictions cannot be relied upon if a VRLA cell has a dry-out condition.

Put another way, to ensure the reliability of this algorithm, equipment or practices (e.g. impedance testing) should be in place to detect VRLA battery dry-out conditions.

However, the test results (on the previous page) also show an unexpected trend at the 85-minute mark. Note how the CRT value drops to 5.6 hours. In a good string, the CRT value will be consistent during a discharge.

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[3] Faster discharge rates will typically yield valid predictions sooner.

Interestingly, this aspect of the algorithm – its sensitivity to changing slope – can be used as another means to flag capacity issues. This can be illustrated by simulating a cell that loses capacity earlier into a discharge as shown below. Applying a voltage loss (middle column) to the CRT, note how the value dips below 1 hour then rebounds to around 3 hours. Any significant change in the CRT warrants an investigation if the load has not changed.

Min	mV	delta	loss	TTE (min)	CRT (hrs)	Slope
	54083		0			
5	49288	4795	0	4	0.1	15.98
10	48790	498	0	34	0.7	1.66
15	48847	-57	0	-300	-4.8	-0.19
20	48845	2	0	8556	142.9	0.01
25	48819	26	0	656	11.3	0.09
30	48784	35	0	485	8.6	0.12
35	47740	1044	1	14	0.8	3.48
40	46692	1048	2	11	0.9	3.49
45	45643	1049	3	9	0.9	3.50
50	44589	1054	4	6	0.9	3.51
55	44535	54	4	117	2.9	0.18
60	44480	55	4	113	2.9	0.18
65	44422	58	4	104	2.8	0.19
70	44365	57	4	104	2.9	0.19
75	44305	60	4	96	2.9	0.20
80	44246	59	4	95	2.9	0.20
85	44184	62	4	88	2.9	0.21
90	44122	62	4	86	2.9	0.21
95	44059	63	4	82	2.9	0.21
100	43995	64	4	78	3.0	0.21
105	43932	63	4	77	3.0	0.21
110	43864	68	4	69	3.0	0.23
115	43797	67	4	67	3.0	0.22
120	43727	70	4	62	3.0	0.23
125	43656	71	4	58	3.1	0.24
130	43580	76	4	52	3.0	0.25
135	43503	77	4	49	3.1	0.26
140	43426	77	4	46	3.1	0.26
145	43342	84	4	40	3.1	0.28
150	43253	89	4	35	3.1	0.30
155	43157	96	4	30	3.1	0.32
160	43050	107	4	25	3.1	0.36
165	42927	123	4	19	3.1	0.41
170	42772	155	4	12	3.0	0.52
175	42490	282	4	4	3.0	0.94
180	40487	2003	4	-2	3.0	6.68

Table 2. Data Adjusted for Simulated 4V Capacity Loss Occurring Early into Discharge

Because the algorithm is sensitive to slope, it can be used to opportunistically detect sudden voltage dips that would occur with premature battery failure.

Finally, it is worth noting that factoring in the 4V capacity loss, the CRT value is close to the actual 3.25-hour reserve capacity. Though only one example, this helps illustrates just how well the voltage-slope algorithm can estimate reserve time.[4] In addition, it remains consistent through the discharge, which is positive indicator.

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[4] The patent contains many other accuracy test results for both newer and older batteries, flooded and vented.

Summary

A new battery rundown test has been proposed. It relies upon the voltage-slope fuel gauge approach to create simpler and more intuitive setup of reserve time (e.g. 8 hr) and percentage threshold (e.g. 80%). This avoids having to use a battery discharge table to select a test duration and test end-voltage. The proposed technique also removes concern about the reliability of the current measurement.

Since fuel gauge reliability is a concern, tests were conducted on an older VRLA string that exhibited capacity loss late into a discharge cycle. The results confirmed expectations – that a rundown test alone cannot detect capacity loss that occurs late into a discharge. Therefore, to ensure the reliability of this fuel gauge algorithm, equipment or practices (e.g. impedance testing) should be in place to detect VRLA battery dry-out conditions.

There is one other beneficial outcome though. Because the algorithm was shown to be sensitive to slope, it can be used to opportunistically detect sudden voltage dips that would occur with premature battery failure. In other words, predictions made early into a discharge may detect failures such as shorts (but not dry-out conditions).

References

1. IEEE Std 450-2010, Recommended Practice for Maintenance, Testing and Replacement of Vented Lead-Acid Batteries for Stationary Applications

2. IEEE Std 1188-2005, Recommended Practice for Maintenance, Testing and Replacement of Valve-Regulated (VRLA) Lead-Acid Batteries for Stationary Applications

3. Thomas D. O’Sullivan, “Method for Predicting Battery Capacity”. U.S. Patent 6,211,654, issued April 3, 2001.

Appendix - Table 3. Data for Discharge Curve of 25Ah Battery using 4A Load

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115	47797	67	216	5.5	0.2233	
120	47727	70	205	5.4	0.2333	
125	47656	71	199	5.4	0.2367	
130	47580	76	184	5.2	0.2533	
135	47503	77	179	5.2	0.2567	
140	47426	77	176	5.3	0.2567	
145	47342	84	159	5.1	0.2800	
150	47253	89	148	5.0	0.2967	
155	47157	96	134	4.8	0.3200	
160	47050	107	118	4.6	0.3567	
165	46927	123	100	4.4	0.4100	
170	46772	155	77	4.1	0.5167	
175	46490	282	40	3.6	0.9400	
180	44487	2003	3	3.1	6.6767	2V loss in 5 minutes!
185	44098	389	13	3.3	1.2967	
190	43210	888	3	3.2	2.9600	Rapid loss resumes and accelerates!
195	41912	1298		3.3	4.3267	End voltage reached.