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Improvement of failure detection of production line test results by implementing ΔV criteria

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Abstract

The reliability of automotive batteries is an important factor, especially for the OEM market. To ensure consistent reliability all automotive batteries are subjected to electrical load tests prior to shipment. These tests are performed in accordance with industry accepted standards. It is essential that the energy discharged from the battery during test be minimized to avoid the cost and delay associated with recharge. When defining the ideal high rate discharge test process one must consider these basic requirements.

Immediately after formation, and preferably, after post cleaning, batteries are discharged at high current for a few seconds. The voltage under load at the end of test is determined and compared to nominal values resulting in a pass/fail decision.

This paper discusses the effectiveness of the present high rate discharge test evaluation criteria in terms of it's ability to accurately discriminate between acceptable and unacceptable batteries. Variations in materials and manufacturing processes affect open-circuit voltage (OCV) and constant current voltage (CCV) measurements leading to erroneous pass/fail determinations. The paper will illustrate how these variations can be recognized and statistically evaluated.

A supplemental evaluation criterion is presented which significantly improves the reliability of test results. This criterion is the gradient ΔV of the discharge curve. Evaluation of test data using this criterion yields information that directly correlates to the failure mode of the rejected battery, including irregularities in pasting and assembly.

This paper concludes that the implementation of ΔV criterion significantly improves the failure detection of batteries subjected to production line high-rate discharge tests. Using the ΔV criterion to evaluate the test results is a more accurate determinant of an acceptable battery than the traditional criteria and results in fewer customer returns.

Keywords: Automotive batteries; High rate discharge; Production line test; Evaluation gradient ΔV

1. Introduction

High rate testing has become an integral part of the finish line in battery factories. Each high rate test procedure is developed specific to a battery type and differs from the standardized laboratory tests as defined by IEC, DIN, EN.

Laboratory test procedures as employed to test new battery designs and also used when testing a sample to qualify the production batch are not appropriate for production process testing. These tests are designed to simulate the use of the battery in it's final application. These tests applied to the production process would require too much time to complete and would severely limit output.

Testing in accordance with the laboratory test standard EN 600095-1, for example requires discharging of the battery at a temperature of -18°C with a cold cranking current (I_{cc}) for a minimum time of 150 s, during which the minimum voltage should not be lower than 9 V after 30 s and 6 V after 150 s [1]. Discounting the challenge of regulating temperature, integration of this test into the production process would limit production to 0.4 batteries per minute per line. Typical production rates require throughput 25 times higher. In addition, it would be necessary to replace the discharged energy to ensure that the battery has the correct state-of-charge when delivered. These limitations and constraints are unacceptable in a production environment.

The majority of the battery manufacturers are performing a simplified test on 100% of the production lot which allows for much greater rates of production. The objective of the test is to identify defective batteries, sort those batteries from accepted product and to accomplish this without discharging to the extent that recharge would be necessary.

Immediately after formation, and preferably, after post cleaning, the batteries are discharged at high current for a few seconds. The open circuit voltage before discharge and voltage under load at the end of discharge is determined

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and compared to nominal values resulting in a pass/fail decision.

2. Traditional testing and evaluation methods

Each test profile contains parameters for load current, load time and limits for open-circuit voltage (OCV) and constant current voltage (CCV). The first measurement taken is OCV. The OCV value is used to identify any decrease in the acid density due to formation process irregularities, e.g. sulfation. If the value is within the set tolerances, the load test is performed. Before the end of the load test the final voltage under load (CCV) is determined at the programmed discharge time t_{HRD}. The CCV indicates major defects, e.g. faulty intercell connection weldings (Fig. 1).

Due to variations in materials and manufacturing processes we can expect significant variations in high rate test results. OCV and CCV measured values may drift and vary, exceeding the absolute limits even on acceptable batteries [2].

Variations in test results and long-term drift effects can be attributed to:

- different production lots;
- process time between end of formation and discharge test;
- different battery temperature during formation;

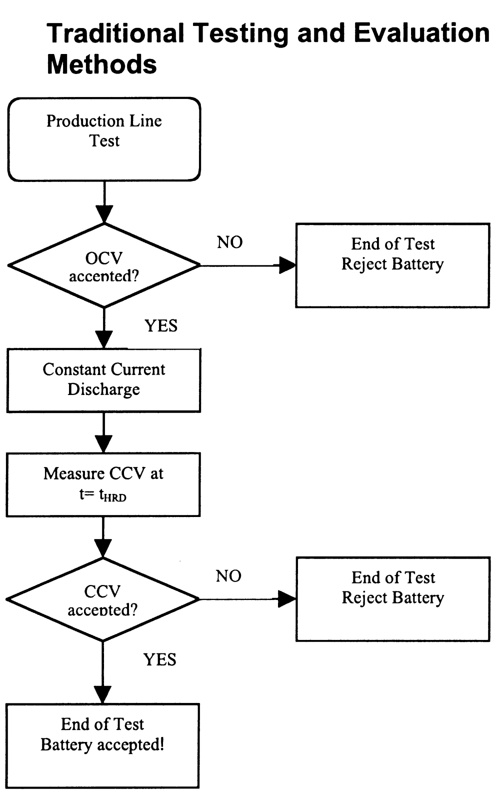

Fig. 1. Flow chart of traditional production line test.

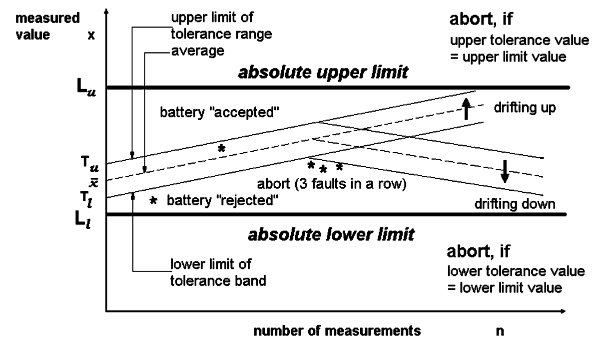

Fig. 2. Limits, tolerance range.

- pre-manufacturing tolerances on pasting, drying and curing;
- differences between charging rectifiers during formation.

To account for these variations a tolerence band which follows the drift is calculated by programmable factors and average values of voltage measurements.

After each test with the result ‘‘accepted’’, the averages and the standard deviations of OCV and CCV are calculated by a programmable number of measurements. The tolerance band can now be derived from the equations:

$$T_{\mathrm{upper\,limit}} = U_{\mathrm{AVG}}\left(1 + \frac{k}{100}\right) \quad (1)$$

and

$$T_{\mathrm{lower\ \ limit}} = U_{\mathrm{AVG}}\left(1 - \frac{k}{100}\right) \quad (2)$$

where U_{AVG} reflects the calculated average value of the voltage measurements and k the programmed percentage in the test profile.

A correct selection of the k-factor is important, as all batteries with voltage values outside the tolerance range will be ‘‘rejected’’ and in case of a drifting value, the entire test lot will be aborted if the tolerance range exceeds the absolute limit values. These relationships are shown in Fig. 2.

In practice, some more details must be taken into account for evaluation:

- contact faults;
- polarity;
- load current deviation;
- battery temperature.

3. Experimental

The test profile in Table 1 was conducted under actual production conditions using a Digatron Production Line Tester PLT 1500-12 fitted with an optional Polarity Switch. This equipment allows high rate discharge tests from 0 to 1500 A and 15 to 5 V independent of battery polarity. The software provides detailed information of statistical evaluation.

Table 1
Production line test profile

Parameter	Set value
Cold cranking current I_{cc} (A)	800
Discharge time t_{HRD} (s)	5
OCV absolute upper limit (V)	12.960
OCV upper tolerance k-factor	–
OCV absolute lower limit (V)	12.720
OCV lower tolerance k-factor	–
CCV absolute upper limit (V)	9.500
CCV upper tolerance k-factor	–
CCV absolute lower limit (V)	7.500
CCV lower tolerance k-factor (%)	3
ΔV criteria (V)	0.100
Δt (s)	4
Number of measurements to calculate voltage averages	25

A comparison of the final results when using the traditional evaluation method described in Section 2 versus the improved method using the ΔV criteria is provided below. The experiment below uses data collected during high rate discharge test of a production batch. The following discussion, diagrams and tables relate to a standard automotive battery, type 570024.

The appropriate discharge rate depends on the battery type and design. There is no single high rate discharge test regime applicable to all battery types. Cold cranking currents as required in EN600095-1 are not useful because the test conditions on finishing lines are not comparable to laboratory conditions and the current is too low to identify faulty batteries during a 5 s discharge period. Tests with very high discharge currents (e.g. approximately 1.2 A cm^{-2}) for 2 s have been conducted but have not provided the expected results. The large number of batteries discharged with approximately 0.67 A cm^{-2} per positive electrode for 5 s provided good results but it can only be a rough figure. In practice, one has to consider grid design and paste recipe when determining the discharge current to get optimum results for each battery type.

The test profile includes one k-factor to calculate a lower tolerance value only for CCV. The k-factor is set to 3%. This figure was found empirically and yields sufficiently reliable results. The number of batteries to determine average values are set to 25.

4. Results

In the following, the effectiveness of the present production line test evaluation criteria in terms of it's ability to accurately discriminate between acceptable and unacceptable batteries will be discussed. A tear down analysis of all rejected batteries will compare OCV, CCV and ΔV criteria and their relation to battery defects.

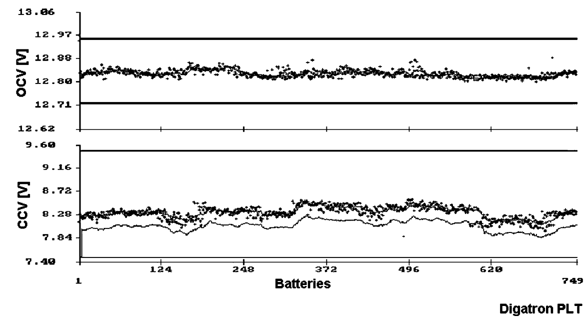

Fig. 3. Evaluated OCV and CCV data of 749 batteries.

The upper diagram in Fig. 3 shows OCV values and the absolute lower and upper limits. The lower diagram in Fig. 3 shows CCV voltages with the calculated lower tolerance limit and the absolute lower limit underneath. The minima and maxima values of the calculated tolerance limits reflects the actual variation attributable to manufacturing tolerances (Table 2).

The very small OCV deviation of 45 mV confirms that the absolute limits can be programmed tightly enough to differentiate between acceptable and unacceptable batteries. In this case one can avoid entering a k-factor. Compared to OCV deviation the CCV deviation of 424 mV needs much more attention. Minima and maxima for the lower CCV tolerance limit can be derived in accordance with Eq. (2).

Minima:

$$T_{lower\ \ limit} = U_{AVG(min)}\left(1-\frac{k}{100}\right) = 8.094\,V\left(1-\frac{3}{100}\right) = 7.851\,V \qquad (3)$$

Maxima:

$$T_{lower\ \ limit} = U_{AVG(max)}\left(1-\frac{k}{100}\right) = 8.518\,V\left(1-\frac{3}{100}\right) = 8.262\,V \qquad (4)$$

The maximum lower CCV tolerance of the entire test run is $8.518 - 8.262 = 0.256$ V for at least one of the next batteries. This would accept all batteries with CCV voltage deviations <0.256 V.

In order to prove the correlation between measured CCV values and defective batteries the following test was

Table 2
Evaluation of average values

Evaluated voltage	Minimum average value (V)	Total average value (V)	Maximum average value (V)
OCV	12.810	12.827	12.855
CCV	8.094	8.263	8.518

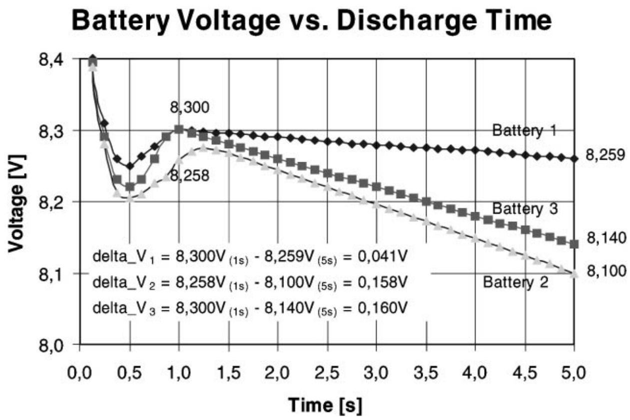

Fig. 4. CCV vs. discharge time of modified batteries. Battery 1: reference battery; battery 2: reverse polarity at one cell; battery 3:50% reduced positive electrodes at one cell.

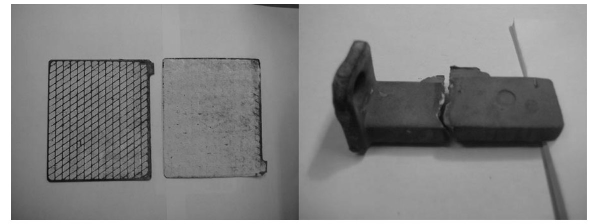

Fig. 5. Sulfated positive electrodes and broken strap.

Table 3
Evaluation ΔV of 749 batteries

Average value ΔV (V)	Maximum accepted ΔV (V)	Not accepted ΔV (V)
0.033	0.063	0.173, 0.126

performed (Fig. 4). The test samples consisted of one battery without any defect and two batteries with typical failure modes.

- Battery 1: reference without failure.
- Battery 2: one cell, reverse polarity.
- Battery 3: one cell, 50% reduced positive electrodes.

The curves can be divided into two phases:

- Phase 1: initial voltage drop with recovery.
- Phase 2: smooth electrochemical conversion.

Phase 1 is substantially influenced by the sudden acid depletion in the pores of the active mass and the delayed formation of lead sulphate crystals as well as ohmic losses. Phase 2 begins after passing the initial voltage drop when the voltage is for a moment in a relatively stable state. The "outer" acid is now diffusing into the pores of the active mass and there is a smooth electrochemical conversion of lead to lead oxide [3].

In this example, the initial voltage drop (phase 1), occurs between 1 and 1.2 s. From this moment on, the voltage curves develop quite differently. One will notice that the curves of the defective batteries do not much differ from each other as compared to the reference curve. The significant fact, however, is that none of the defects has caused a voltage difference of >0.256 V. The traditional test method would have accepted these batteries for shipment.

In our experiment we have determined the gradients of the voltage curves for phase 2 and tested them for a maximum admissible ΔV of 0.100 V (Table 3).

The first value CCV_1 is measured at

$$t_{CCV1} = t_{HRD} - \Delta t = 5\,s - 4\,s = 1\,s \quad (5)$$

The second value CCV_2 is measured at

$$t_{CCV2} = t_{HRD} = 5\,s \quad (6)$$

The ΔV can now be derived from Eq. (7)

$$\Delta V = CCV_1 - CCV_2 \quad (7)$$

The tear down analysis of the two batteries which were not accepted by ΔV reveals that battery no.2 had one broken strap with $\Delta V = 0.173\,V$ and battery no. 723, exhibited excessive sulfation of the positive electrodes with $\Delta V = 0.126\,V$ (see Fig. 5). Tables 4 and 5 clearly point out: these batteries would have been accepted without testing ΔV.

The results of the above experiment with 749 batteries, type 57024, could be confirmed by further tear down analysis of different production lots. The following tables contain test results of batteries which would be accepted using traditional evaluation criteria but did not pass when subjected to ΔV criteria. Tables 6–9 represent a different analysis and a different battery type.

Table 4
Battery no. 2, test results

	Measured value (V)	Lower limit (V)	Upper limit (V)	Test result
OCV	12.951	12.720	12.960	Accepted
CCV	8.157	7.500	9.500	Accepted
ΔV	0.173		0.100	Not accepted

Table 5
Battery no. 723, test results

	Measured value (V)	Lower limit (V)	Upper limit (V)	Test result
OCV	12.890	12.720	12.960	Accepted
CCV	8.327	7.934	9.500	Accepted
ΔV	0.126		0.100	Not accepted

Table 6
Tear down analysis battery 543025, $I = 700$ A, $t = 5$ s[a]

	Measured value (V)	Lower limit (V)	Upper limit (V)	Test result
OCV	12.754	12.720	12.960	Accepted
CCV	7.930	7.500	9.500	Accepted
ΔV	0.245		0.100	Not accepted

[a] Tear down analysis: wrong polarity at cell 3.

Table 7
Tear down analysis battery 570091, $I = 900$ A, $t = 5$ s[a]

	Measured value (V)	Lower limit (V)	Upper limit (V)	Test result
OCV	12.825	12.720	12.960	Accepted
CCV	8.510	7.500	9.500	Accepted
ΔV	0.196		0.100	Not accepted

[a] Tear down analysis: grids without bottom frame at negative electrodes on cell 5 and 6.

Table 8
Tear down analysis battery 600048, $I = 1000$ A, $t = 5$ s[a]

	Measured value (V)	Lower limit (V)	Upper limit	Test result
OCV	12.820	12.720	12.960	Accepted
CCV	7.670	7.500	9.500	Accepted
ΔV	0.168		0.100	Not accepted

[a] Tear down analysis: bad interface: grid (negative) PAM on all positive electrodes.

Table 9
Tear down analysis battery 574015, $I = 700$ A, $t = 5$ s[a]

	Measured value (V)	Lower limit (V)	Upper limit (V)	Test result
OCV	12.740	12.720	12.940	Accepted
CCV	8.280	8.000	9.500	Accepted
ΔV	0.150		0.100	Not accepted

[a] Tear down analysis: short circuit on cell 1: contact between one positive electrode and negative strap.

5. Conclusion

The traditional test method evaluating OCV and CCV can only detect major faults of entire batteries. The voltage deviation of minor defects which relate to single cells or electrodes are too small to differentiate between process tolerances and faulty batteries.

The limits for OCV and CCV must be adapted to the design and the production tolerances in order to obtain an informative evaluation on the one hand and to recognize and sort out all faulty batteries safely on the other hand. The k-factor in addition allows tightening the limits by calculating a tolerance band which will follow process drifts. There is no doubt that these parameters are the most critical parts of the traditional test profile. If the tolerance band is very tight too many good batteries are rejected if they do not follow the drift due to manufacturing tolerances. If the tolerance band is wide enough to cover most of the drifts and manufacturing tolerances minor faults cannot be detected. But even the so called minor faults may cause undesired customer returns on a long term view.

By the optimization of the process times and, in particular, by the reduction of the rest periods between the end of formation and the production line test, the traditional method is turning out more and more critical. It is important to realize that OCV is at it's highest value immediately after formation. VRLA batteries especially need very long rest periods after formation so that OCV reports the exact acid density.

The experience with the implementation of ΔV in production line tests has fully confirmed the theoretical considerations. The percentage of batteries rejected when evaluated by ΔV is approximately 25% of all rejected batteries. These are batteries, which would have been shipped to customers.

Considering that VRLA batteries will probably replace the traditional flooded type in most applications the evaluation of ΔV may become of greater importance on production line tests.

This paper concludes that the implementation of ΔV criteria significantly improves the failure detection of batteries subjected to production line high-rate discharge tests. Manufacturers might consider adapting this improved test criterion.

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