Influence of the Rest Period on the Charge Released by a Lead Acid Battery

SEPTIMIU MISCHIE, LIVIU TOMA
Faculty of Electronics and Telecommunications
Politehnica University of Timisoara
Vasile Parvan Street 2, 300223 Timisoara
ROMANIA

Abstract: - This paper presents the characteristics of a lead acid battery regarding the charge that it can release. It is desired to determine the effect of the rest period on the charge released by the battery. For this purpose a series of experiments that contain at least one rest period are presented. In each of them the charge released is counted, depending on the time when the rest period is started. It is pointed out that, every battery can release a charge equal with its rated capacity if the discharge contains rest periods.

Key-Words: - Lead acid battery, Charge released, Rest period, Charge available

1 Introduction

Lead-acid batteries are among the most used devices to store and deliver energy. These batteries can contain one cell, or more probably, two or more cells connected in series. The nominal voltage of a cell is 2 V.

The *theoretical* or *rated* capacity of a battery is the total amount of charge, in Ah (Ampere-hours), that can be withdrawn from a fully charged battery. Sometimes, this parameter is referred to as C_n, which is the capacity at a particular discharge rate or current such the battery is depleted in n hours [1]. This means that, if the discharge current is C_n/n, then the charge released is C_n. This current is named nominal discharge current.

The charge that a battery can release depends basically on the discharge current [2]-[4] and is named *usable capacity*, C_u. The higher the discharge current, the lower the usable capacity. The Peukert equation [1] presents this dependence:

$$C_u = cI^b, \qquad (1)$$

where I is the discharge current, while a and b, b<0, are constants that can be obtained by experiments.

The usable capacity depends also on the temperature, age of the battery, previous discharge or charge.

Another parameter of a battery is the *open circuit voltage* (*OCV* or U_{oc}): the voltage across the terminals when there is no current flowing through it. In order to obtain the *OCV*, a time interval (30 min-2 hours) is necessary, because this voltage will drift a certain period of time after the current has became zero. The time interval when the battery neither receives nor delivers current is named *rest period*.

State of Charge (*SOC*) is a disputed parameter of a battery. Thus, in [2] and [3], SOC is presented as a dimensionless ratio of the available charge, Q_{av} with respect to the total or initial charge, Q_{ini}. If the available charge is expressed by difference between initial charge and charge released by battery, Q_{rel}, then *SOC* is

$$SOC = \frac{Q_{av}}{Q_{ini}} = \frac{Q_{ini} - Q_{rel}}{Q_{ini}}. \qquad (2)$$

On the other hand, in [4], *SOC* is presented as the state a battery is in. It indicates the concentration of acid in the electrolyte. By lowering the rate of discharge, the battery can release more charge even at the same *SOC*.

However, a fully charged battery has *SOC*=1 and a depleted battery has *SOC*=0.

In order to determine *SOC* by (2), the amounts Q_{ini} and Q_{rel} must be known.

Q_{ini}, which is actually C_u, depends on the discharge rate, as previously presented. Battery manufacturers give discharge curves for various discharge rates. By using these data sheets, the value of Q_{ini} can be obtained. Also, in [2] is presented a method to obtain Q_{ini}. Thus, when the load is connected to the battery terminals, the voltage across it has a drop. The drop's value reflects the level of charge that the battery can release on the load, that is Q_{ini}. Both methods are applicable only if the discharge rate is constant.

Q_{rel} can be computed by coulometric measurement or ampere-hours counting. Thus, if $i(t)$

is the discharge current, Q_{rel} can be computed at each time τ by

$$Q_{rel}(\tau) = \int_0^\tau i(t)dt \,. \qquad (3)$$

If the discharge rate is constant, I, then the charge released can be obtained as the product of I and current time τ.

Another method for *SOC* computing [2] is based also on coulometric measurement, and finds a relation between discharge voltage and SOC. This method is applicable for constant discharge current, too.

The charge released is computed in [6] as follows

$$Q_{rel}(\tau) = \int_0^\tau k[i(t)]\, i(t)dt \,, \qquad (4)$$

where $k[i(t)]$ depends on the discharge current, and is 1 for nominal discharge current and, respectively, greater than 1, when discharge current is higher than the nominal one. Thus, the initial charge is C_n and the charge released can be C_n even if the discharge current is higher than the nominal one. This solution is applicable for variable discharge current.

It must be noted that the value of C_n and also Q_{ini} will be reduced by aging the battery. In [6] is presented a method for Q_{ini} computation that is based on a discharge at the nominal current.

The *OCV* is an accurate indicator of *SOC* for lead-acid batteries, because its value is function of the concentration of acid in electrolyte. It is known that a value in the range the 1.90,…,1.95 V per battery cell corresponds to a depleted battery (*SOC*=0) and a value in the range 2.10,…,2.15 V corresponds to a fully charged battery (*SOC*=1), [4]-[7].

A discharge voltage versus time curve of a lead acid battery contains three regions: the first region contains a voltage increase of about 10-20 mV, lasting a few minutes; the linear region is the most important having the longer time; during the third (hyperbolic) region, the voltage decreases more rapidly. In the third region, it is defined U_{end} at the knee of the curve. Thus in [2] and [3] is considered U_{end} =1.85 V per cell, and in [6] U_{end} is 1.75 V for discharge rates close to the nominal one, and a bit lower for higher discharge rates. U_{end} is the voltage where the *SOC* is considered zero, or battery is depleted, but not fully discharged. The battery can be discharged beyond this point, but only a small part of theoretical capacity can be released. Moreover, it can be damaged and its cycle life will be decreased.

In [4] and [9] is presented the idea that a battery can release more charge if the load is disconnected for some time, before U_{end} is reached, but does not give other information.

This paper presents the influence of the rest period on the charge that a battery can release. Two cases will be presented. First, the rest period is introduced when the voltage across the battery is U_{end}, and next, a few discharges will be realized without the battery being charged. Each of these discharges will be preceded by the same rest period. The total amount of charge released will be evaluated. Second, the rest period is introduced before U_{end} is reached, and next one more discharge is realized, until the voltage become U_{end}. The total amount of charge released until U_{end} is reached will be evaluated depending on value of discharge voltage at the time when the rest period is started.

2 Experiments which emphasize Behavior of the Battery after the Rest Period

This section presents several experiments which have been achieved in order to emphasize the behavior of the battery after the rest period. Each experiment starts when the battery is fully charged and contains one or more discharges. A discharge starts when the load is connected and lasts until the load is disconnected, or the rest period starts. During every discharge, the load is a resistor with a constant value. It follows that the current decreases slowly, similar with discharge voltage. In each experiment, the total amount of charge released is computed.

The battery under test has a rated capacity of 3.3 Ah (at 20 hours) and a nominal voltage of 6 V. According with those in section 1, when the battery is fully charged its OCV could be 3×2.15 V =6.45 V, and respectively, 3×1.9 V=5.7 V when the battery is depleted.

During all the experiments, the voltage across the battery and the current through the battery are acquired with a HP3455 voltmeter and a Voltcraft M-4650CR multimeter. The two instruments are controlled by a computer via an IEEE 488 interface and, a RS-232 interface, respectively.

2.1 The rest period starting at U_{end}

In section 1 it was shown that the usable capacity depends on the discharge rate. In order to validate this affirmation, four discharges at different rates have been achieved, each of them for a different value of the resistive load. In each case the battery was fully charged. Also, each discharge was stopped at U_{end} =5 V. Fig. 1 presents the four discharges. Also, in table 1 the following values are presented for each discharge: the initial current I_{ini}, the charge released, Q_{rel}, computed by (3), and the open circuit voltage after two hours of rest period, $U_{OC,\ r}$. From table 1 it can be seen that the lower the charge released, the higher $U_{OC,r}$. It follows the possibility for the battery to release charge again, especially for higher values of $U_{OC,r}$. It means that, at time when the discharge voltage is 5 V, the *SOC* is 0, and after a long enough rest period, *SOC* becomes again higher than 0.

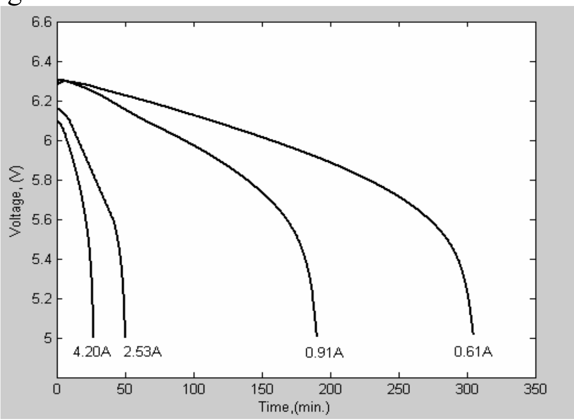

Fig.1 Discharge voltage versus time characteristics at different rates.

Table 1
Results for discharges from Fig.1

I_{ini}[A]	Q_{rel} [Ah]	$U_{oc,r}$[V]
0.61	2.78	5.73
0.91	2.62	5.80
2.53	2.11	5.96
4.20	1.80	6.09

In order to emphasize the charge released after the rest period starting at U_{end}, the following experiments were achieved. Each experiment contains a first discharge, at a certain rate (the initial current is I_{ini}), that is named the main discharge, and is stopped at U_{end}=5 V. After a rest period of 2 hours, another discharge, named additional, is started. This discharge is stopped at U_{end}=5 V, too. The additional discharge is repeated twice, third or fourth times. Each of additional discharges is achieved at the same rate, by using a load with the resistance of 6.7 Ω.

In tables 2-5, for each discharge of the four experiments are presented: initial open circuit voltage $U_{OC,i}$ and the same amount after a 2 hours of rest period, $U_{OC,f}$, as well as their difference, ΔU_{OC}, and the charge released, Q_{rel}. Also, for each experiment, the total amount of charge released, Q_{total}, as sum of all the discharges, is presented.

Table 2
Results for experiment with I_{ini}=4.20 A

Type of discharge	Q_{rel} [Ah]	$U_{OC,i}$ [V]	$U_{OC,f}$ [V]	ΔU_{OC} [mV]
Main	1.80	6.57	6.09	480
Additional1	0.82	6.09	5.85	240
Additional2	0.174	5.85	5.81	40
Additional3	0.169	5.81	5.75	60
Additional4	0.073	5.75	5.72	30
Q_{total}	3.036			

Table 3
Results for experiment with I_{ini}=2.53 A

Type of discharge	Q_{rel} [Ah]	$U_{OC,i}$ [V]	$U_{OC,f}$ [V]	ΔU_{OC} [mV]
Main	2.11	6.55	5.96	590
Additional1	0.478	5.96	5.81	150
Additional2	0.132	5.81	5.77	40
Additional3	0.105	5.77	5.74	30
Additional4	0.066	5.74	5.71	30
Q_{total}	2.891			

Table 4
Results for experiment with I_{ini}=0.91 A

Type of discharge	Q_{rel} [Ah]	$U_{OC,i}$ [V]	$U_{OC,f}$ [V]	ΔU_{OC} [mV]
Main	2.62	6.58	5.80	780
Additional1	0.174	5.80	5.75	50
Additional2	0.096	5.75	5.73	20
Additional3	0.070	5.73	5.70	30
Q_{total}	2.954			

Table 5
Results for experiment with I_{ini}=0.61 A

Type of discharge	Q_{rel} [Ah]	$U_{OC,i}$ [V]	$U_{OC,f}$ [V]	ΔU_{OC} [mV]
Main	2.78	6.55	5.73	820
Additional1	0.088	5.73	5.70	30
Additional2	0.066	5.70	5.67	30
Q_{total}	2.934			

By analyzing experimental results from tables 2-5, the following conclusions can be presented:

-if there are long enough rest periods between discharges, the total amount of charge released by a battery is the same, regardless of the discharge rate, being close to C_n; there are some small differences, depending on the initial level of charge, that depends on the $U_{OC,i}$.

-the highest amount of charge is released in the main discharge and in first additional discharge; for these discharges, the decreasing in open circuit voltage is proportional with the charge released-see also the table 6, only for main discharges.

Table 6
ΔU_{OC} with respect to Q_{rel}

I_{ini} [A]	ΔU_{OC} /Q_{rel} [V/Ah]
4.24	0.267
2.53	0.278
0.915	0.298
0.615	0.294

-for this battery, the open circuit voltage is about 6.56 V when it is full charged and, respectively, about 5.70 V when it is depleted.

2.2 The rest period starting before U_{end}

In this subsection, the influence of the rest period concerning the total amount of charge released by the battery until the first reach of U_{end} will be studied. For this purpose, several experiments were achieved. Each experiment contains a first discharge that is stopped at a certain value of the load or discharge voltage, which is higher than 5V. Then, after 1 hour of rest period, the discharge is resumed until the U_{end} = 5 V is reached. All the discharges have been made at the same rate, by using the load with resistance of 2.35 Ω. For each of these experiments, the total amount of charge released is computed and is compared with the charge released by a discharge without rest period (it is achieved at the same rate, and is stopped at U_{end}=5 V).

In table 7, for each experiment are presented: the initial open circuit voltage, $U_{OC,i}$, the load voltage at time when the rest period is started, U_{load}, the charge released, Q_{rel}, as well as time t_{end} when U_{end} is reached. For a better comparison with the discharge without rest period, t_{end} does not contain the length of the rest period.

Table 7
Results for experiments with rest period before U_{end}

$U_{OC,i}$[V]	U_{load} [V]	Q_{rel}[Ah]	t_{end}[s]
6.56	5,25	2.25	3650
6.56	5.55	2.20	3568
6.56	5.85	2.17	3432
6.56	6.15	2.09	3315
6.56	U_{end}	2.08	3310

From the results presented in table 7 it follows that the nearer U_{load} to U_{end} =5 V, the higher the charge released. In order to explain this result, time variation of voltage across the battery during the rest period and after the rest period must be analyzed.

The variation of voltage during the rest period contains the jump voltage that appears at the time when the load is disconnected, U_1, and then, the exponential variation that follows the jump. In fig.2, this variation, when the rest period is started at U_{load}=5.25 V, is presented. U_2 is the amplitude of exponential variation of voltage.

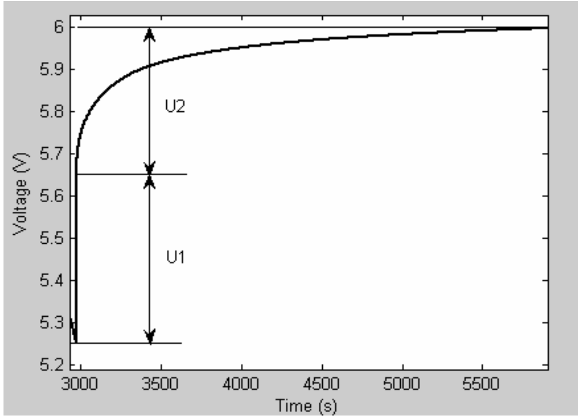

Fig.2 Variation of voltage across the battery during the rest period

In table 8, the amounts U_1, and U_2 and their sum are presented for each experiment.

Table 8
Results obtained based the variation of voltage during the rest period

U_{load} [V]	U_1 [V]	U_2[V]	U_1+U_2 [V]
5.25	0.39	0.36	0.75
5.55	0.27	0.23	0.50
5.85	0.20	0.15	0.35
6.15	0.25	0.08	0.33

Thus, based on results from table 8 it follows: the jump voltage U_1 is higher as U_{load} is closer to U_{end}; also, the voltage increases more after the jump in the remainder part of the rest period, when U_{load} is closer to U_{end}; finally, it follows the highest increasing U_1+U_2, when U_{load}=5.25 V.

On the other side, U_1 can be written as

$$U_1 = U_{OC} - U_{load}, \qquad (5)$$

where U_{oc} is the first measured value of voltage when the current through the battery is zero, and U_{load} is the last measured value when the current is different to zero. If the current value is I, the amount

$$R_i = (U_{OC} - U_{load}) / I, \qquad (6)$$

represents the internal resistance of the battery.

In [5] it is shown that the internal resistance of the battery increases as the battery becomes depleted, or the load voltage closes to U_{end}. This is a justification why the voltage drop U_1 is higher when the battery becomes depleted.

Fig. 3 presents the variation of voltage after the rest period (with solid line) for the experiment with U_{load}=5.25 V, in comparison with discharge without rest period (with dotted line).

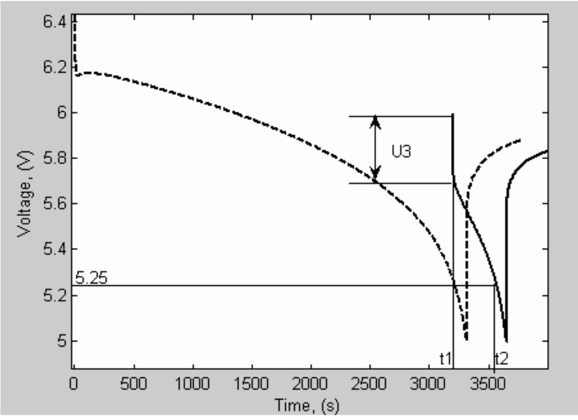

Fig.3 Variation of voltage across the battery after the rest period in comparison with discharge without rest period.

In this figure, t_1 is the time when the load is connected again, t_2 represents the time when the load voltage reaches the value that it had when the load was disconnected (5.25 V), and U_3 is the drop voltage that appears when the load is connected.

In table 9, for each experiment are presented: the difference t_2-t_1, as well as the difference between t_{end} and the amount of 3310 s (this is t_{end} for discharge without rest period) and U_3.

Table 9
Results obtained based the variation of voltage after the rest period

U_{load}[V]	t_2-t_1[s]	t_{end}–3310 [s]	U_3 [V]
5.25	368	340	0.24
5.55	321	258	0.21
5.85	249	122	0.21
6.15	106	5	0.22

It can be seen that the drop U_3 is about the same for all the experiments. It follows that the total increase in voltage due to the rest period, $U_1+U_2-U_3$, is the highest for U_{load} =5.25 V. Also, after rest period, the voltage varies a bit faster in comparison with the case when does not contain the rest period. That is, the gain obtained during the rest period by increasing the U_{OC} is a bit reduced due to the following discharge.

3 Interpretation of the experiments

Based on experiments that were presented in section 2, it follows some conclusions.

The charge released by a battery does not depend on the discharge rate if there are rest periods between discharges. Its value is always close to C_n.

As the time interval of the discharges, including rest periods, is longer, the charge released increases. For instance, each experiment in section 2.1 lasts about 9 hours and allows about 3 Ah of charge released.

The charge released is limited due to diffusion rate of electrolyte. If there are rest periods between discharges, the electrolyte has more time do diffuse into the pores, and thus the battery can release more charge. In order that this property to be more evident, the rest period has to be started when the battery is near depletion.

During the battery discharging, the available charge is

$$Q_{av}(t) = C_u - Q_{rel}(t), \qquad (7)$$

where C_u depends on the discharge rate.

During the rest period, the available charge increases, depending on the time when the rest period starts.

1. The rest period is started at t=t_{end} when $U_{load}(t_{end})$=U_{end}=5V. At that time, $Q_{av}(t_{end})$=0.
During the rest period, $Q_{av}(t)$ increases:

$$Q_{av}(t) \in [0, C_n - Q_{rel}(t_{end})], t \geq t_{end}, \qquad (8)$$

having higher values as the time increases.

2. The rest period is started at t=t_p, when $U_{load}(t_p)$>5V. At that time, $Q_{av}(t_p)$>0. During the rest period, t>t_p, $Q_{av}(t)$ increases:

$$Q_{av}(t) \in [Q_{av}(t_p), C_n - Q_{rel}(t_p)],\ t \geq t_p, \qquad (9)$$

having higher values as the time increases, and difference $U_{load}(t_p)$−5V decreases.

The property of the battery to release charge after a rest period starting when $Q_{av}(t_{end})$=0 is important in practice especially when the rate of the next discharge is less than that in the main discharge.

Also, the systems for determining SOC have to take into account the increase of Q_{av} during the rest period. This increase is higher if the rest period is done to a load voltage close to U_{end}.

4 Conclusion

The paper presents a lot of experiments that emphasize behavior of the battery during and after the rest period. Based on these experiments it follows that the battery can release more charge if the discharge contains rest periods. As the rest period is started when the battery is near depletion, the charge released is higher. It is proposed a simple expression for variation of the available charge during rest period. In the future, a mathematical model of the battery, that allows computation of available charge depending of the time when the rest period is started and the length of rest period, could be achieved.

References:

[1] N.R.E. Laboratory, Advanced Vehicle Simulator (ADVISOR), USA, 2002

[2] A. Anbuky and P. Pascoe, VRLA Battery State-of-Charge Estimation in Telecommunications Power Systems, *IEEE Trans. on Industrial Electronics*, Vol.47, No.3, 2000, pp. 565-573.

[3] P. Pascoe and A. Anbuky, VRLA Battery Discharge Reserve Time Estimation, *IEEE Trans. on Power Electronics*, Vol.19, No.6, 2004, pp. 1515-1521.

[4] J. Aylor, A. Thieme, B. Johnson, A Battery State-of-Charge Indicator for Electric Wheelchairs, *IEEE Trans.on Industrial Electronics*, Vol.39, No.5, 1992, pp. 398-409.

[5] M. Durr, A. Cruden, S. Clair, J.R. McDonald, Dynamic model of a lead acid battery for use in a domestic fuel cell system, *Journal of Power Sources*, Vol.161, No.2, 2006, pp. 1440-1411.

[6] K. Kutluay, Y. Cadirci, Y. Ozkazanc, I. Cadirci, A New Online State-of-Charge Estimation and Monitoring System for Sealed Lead-Acid Batteries in Telecommunication Power Supplies, *IEEE Trans.on Industrial Electronics*, Vol.52, No.5, 2005, pp. 1315-1327.

[7] S. Piller, M. Perrin, A. Jossen, Methods for state-of-charge determination and their applications, *Journal of Power Sources*, Vol.96, 2001, pp. 113-120.

[8] H. Chan, D. Sutanto, A New Battery Model for use with Battery Energy Storage Systems and Electric Vehicles Power Systems, *IEEE Power Engineering Society Conference*, vol. 1 Singapore, January 2000, pp. 470-476.

[9] X. Wang, T. Stuart, Charge Measurement Circuit for Electric Vehicle Batteries, *IEEE Trans.on Aerospace and Electronic Systems*, Vol.38, No.4, 2002, pp. 1201-1208.