

Consequences of Deep Cycling 24 Volt Battery Strings

Henry A. Catherino
Oakland University

Fred Feres
Exide Technologies

ABSTRACT

Deep charge and discharge cycling of 24 Volt battery strings composed of two 12 Volt VRLA batteries wired in series affects reliability and life expectancy. This is a matter of interest in vehicle power source applications. These cycles include those specific operational cases requiring the delivery of the full storage capacity during discharge. The concern here is related to applications where batteries serve as a primary power source and the energy content is an issue. It is a common practice for deep cycling a 24 volt battery string to simply add the specified limit voltages during charge and discharge for the individual 12 Volt batteries. In reality, the 12 Volt batteries have an inherent capacity variability and are not identical in their performance characteristics. The actual voltages of the individual 12 Volt batteries are not identical. The experimental measurements reveal that one of the two individual batteries in the series configuration is driven to voltages exceeding the acceptable operational limits for a single 12 Volt battery. This condition results in a loss of battery capacity during cycling and results in early string failure because of cell reversals. This condition appears whenever the battery polarization is determined by a single cell rather than being shared by a number of cells that are presumed to be matched.

CITATION: Catherino, H. and Feres, F., "Consequences of Deep Cycling 24 Volt Battery Strings," *SAE Int. J. Alt. Power*, 4(2):2015, doi:10.4271/2015-01-9142.

INTRODUCTION

This paper addresses the technical issues related to the deep cycle testing of 24 Volt battery strings composed of two 12 Volt AGM military grade 120Ah batteries wired in series.

It is noteworthy to make the following general observation. This study may appear to have a very narrowly focused objective. However, it needs to be pointed out that the issues raised in this paper apply to all multi-celled batteries and is independent of the chemistries involved. Only casual mention shall be made of these other battery systems except to point out the common connection. One obvious connection of current concern is the 28 Volt lithium ion batteries. The discussion that follows also applies to that battery design.

A comment regarding the uniqueness of this observation is in order. Over the years, considerable work has been performed on high voltage battery strings. It is very likely that this problem has been observed by many workers in the field. The difficulty that arises is that such news is not particularly good. It focuses on system failures and not successes. These observations are usually kept as proprietary information while methods are developed to deal with the situation. The concept of a smart battery has been around for a long time and its development has been largely pushed by the development of lithium ion pack due to their well-known safety problems. It is necessary to emphasize the point that data indicating the nature of the problem is critical for the issuance of user specifications that can ensure better

and more reliable system performance of purchased hardware. It is in this perspective that the study that follows addresses and elucidates a critical issue that is important to the wider user community. No doubt that there are many specialists that are already aware of this issue but there are many more users that need to know. These users have no documented basis for understanding the existence of the problem. This issue has been previously reported but very little public attention has been given to it [1].

DISCUSSION

The Society of Automotive Engineers Standard for testing automotive 12 Volt storage batteries (SAE J 537) and the military version for deep cycle testing of 12 Volt 120Ah 6TAGM batteries (MIL-PRF-32143B), specifies that the end of discharge termination takes place at 10.5 Volts [2,3].

The end of charge voltage is 14.7 Volts (and 14.5 Volts for reserve capacity testing). It is to be noted that this specification applies only to single 12 Volt AGM batteries. There currently exists no formal specification governing the performance of the series-wired combination of two 12 Volt batteries.

The charging voltage applied by the power source to a single 12 Volt battery is specified by the battery manufacturer for optimal performance. The selected charging voltage will charge the battery but, at the same time, it serves to minimize heat generation and gas

production within the battery. Although the battery is said to be recombinant, some small hydrogen evolution takes place and it does not undergo recombination at a rate that is of any significance. The accumulated hydrogen gas is occasionally vented from the battery. It is to be noted that the selective venting of hydrogen and the recombination of oxygen discharges the negative electrode but not the positive electrode. An asymmetric change in the state of charge results. The net result is water loss that takes place slowly over the life of the battery. During the constant voltage charging of a single 12 Volt battery, the end of charge (EOC) voltage is identical with the applied constant voltage by the charging power source. Operationally, the entire charging process takes place at constant voltage except during very early stages of the charging process. This transient effect often occurs when a battery is in a deeply discharged condition. In that case, the current demand at the preset voltage limit sometimes exceeds the power delivery capability of the charging power supply. The charging takes place at constant power until the rising voltage of the battery limits the charging power demand and the battery then continues charging at a constant applied voltage.

The end of discharge (EOD) voltage selection is slightly more complicated because of the attempts to explain it in oversimplified terms. A discharge curve for a 6TAGM battery is shown in Figure 1. The discharge rate is C/20 and the discharge termination takes place at 10.5 Volts. It is often said that allowing the voltage to drop further gives no significant increase of capacity so the 10.5 Volt limit is a standardized value that is commonly used in testing. However, that discharge voltage limit was selected for a very specific reason. Figure 2 shows the battery presented in Figure 1 but this time the voltages across each of the six cells composing the battery have been monitored. It is clear that one of the cells has gone into a deep discharge while the others have not yet significantly dropped in voltage. In this case, the battery voltage is determined by the cell having the smallest capacity compared to the other cells composing that battery. It is evident that should the battery voltage drop lower than 10.5 Volts, the cell having the smallest capacity can be forced into reversal. That is, the cell could be made to charge in the reverse direction while the battery is discharging. This is detrimental to the cell and causes that cell to rapidly deteriorate. Driving the battery voltage lower than 10.5 Volts can serve to reduce the reliability and life of the battery. There is a finite probability that each of the cells has identical capacities. In that case and only in that case the battery can be deeply discharged without harm to the battery. However, an assemblage of a set of matched capacity cells is extremely rare and it also constitutes a very low probability event. The behavior shown in Figure 2 is actually a worst case situation during discharge. It should be clear that discharging the battery below 10.5 Volts in this kind of testing can be detrimental to the battery life expectancy.

It is to be noted that the observation that cell reversal is detrimental is often stated as an empirical fact in the manufacturer's literature. Later in this paper a commentary is given that attempts to speculate on the mechanisms that may prevail during the reversal of a lead acid cell.

The battery voltage measured across the terminals during discharge is dependent on the current delivered to a load. The cycling experiment in the above discussion applies to a discharge rate of C/20. However, suppose that the load had a resistance equal to the internal resistance

of the battery. This is the max power point of the battery. In that case, the operating voltage would be one-half of the open circuit voltage which is approximately 6 Volts. If a battery monitoring system is set for detecting 10.5 Volts as the end of charge voltage, the control logic has to override this indication so as to permit a battery that is not in a discharged condition to deliver the required current to the load. This could be handled by a logical AND operator where a 10.5 Volt limit AND a state of charge limit indication would determine when to end the discharge.

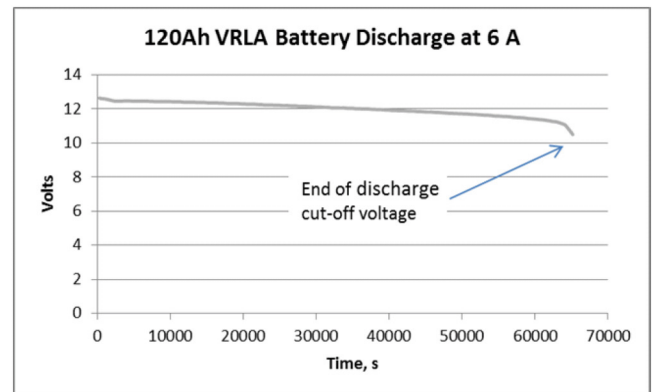


Figure 1. Battery response showing the end of discharge as determined by the cut off voltage selection.

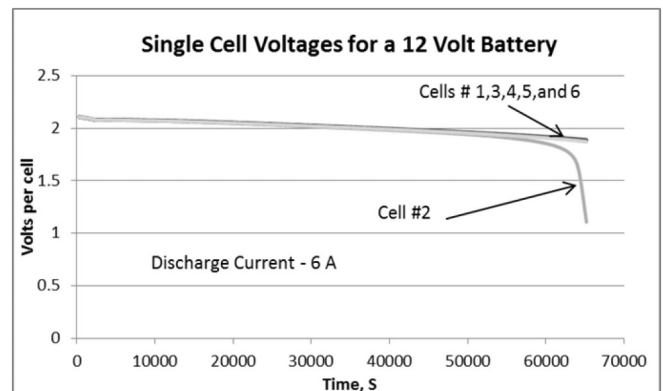


Figure 2. The same battery discharge where the response shown is that of each of the cells composing the battery.

Now consider the case of two 12V batteries operating as a series string. The voltage across the 24V string is the sum of the voltages of both of the batteries. In the case where the string is being charged, the applied constant voltage is distributed between the battery pair as a simple summation:

$$E(\text{applied}) = E(\text{battery 1}) + E(\text{battery 2})$$

During an actual charging, the applied voltage across the string was fixed at 29.4 V. It was intended that each battery have 14.7 V impressed on its terminals; that is,

$$E(\text{battery 1}) = E(\text{battery 2})$$

During a particular test, the data revealed that the voltages across test batteries in a string were $E1 = 15.57$ V and $E2 = 13.84$ V. This corresponds to an imposed charging voltage of 29.41 V. The critical observation here is that battery 1 is operating far outside the acceptable charging voltage as specified by the manufacturer.

This behavior can be attributed to capacity and state of charge equalization differences. A discussion of these effects follows. For the purpose of clarity, the term “equalization” often appears. This term is understood to mean that the string of series connected batteries that are wired together conform to a predefined initial condition. That is, the initial condition might be that the batteries start out in a fully charged condition or, alternatively, they start out in a fully discharged condition. These two conditions can occur simultaneously if and only if the batteries are identical. It is essential to note that this is an extremely rare event. It is well established that the performance of production batteries show operational characteristics that appear to be normally distributed with a definable variance.

Consider first the Ideal Case. Here the batteries are identical in every way. The end of charge (EOC) voltage for each battery is exactly 14.25 V and the end of discharge voltage (EOD) is exactly 10.5 V. Actually this is the usual assumption that is made when operating with battery strings. Figure 3 represents a situation where the battery capacities are identical and the end of charge and end of discharge voltages also are identical.

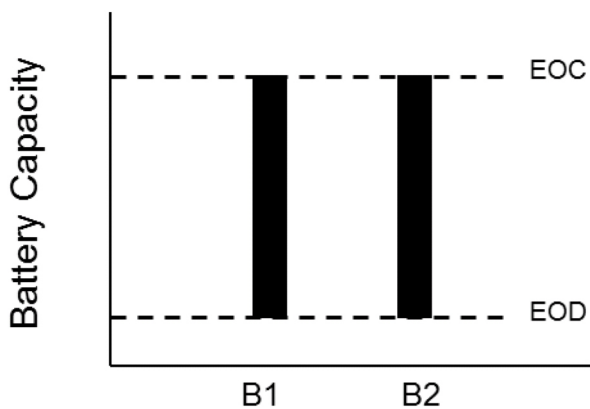


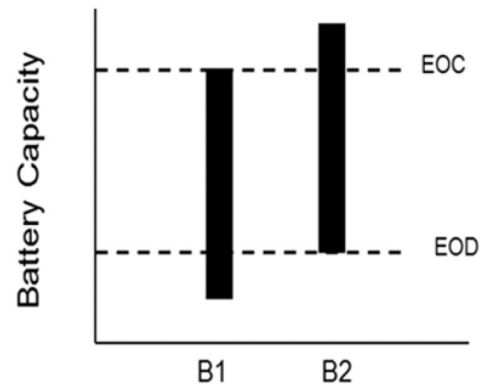
Figure 3. Representation of the “Ideal” condition for battery selection in series strings.

One way of envisioning this is that the batteries have been equalized so that they are fully charged and then cycled such that at the end of charge, the end of charge voltages are identical. The applied voltage during charge is evenly distributed between the batteries in the string. The end of discharge (EOD) voltage set point is 21.0 V where each battery contributes exactly 10.5 V each.

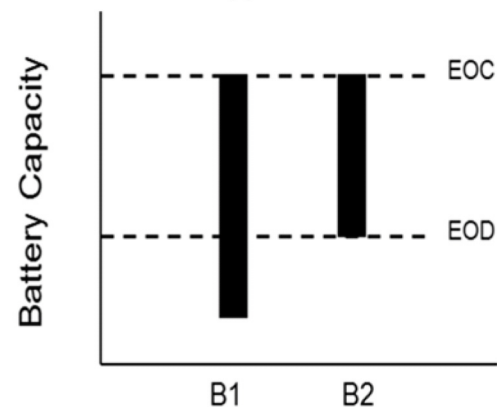
It is a common engineering practice to project the performance of this battery string by simply doubling the properties of any single AGM battery. That is, two batteries in series have twice the voltage and two batteries have twice the rated energy content of one battery. Unfortunately, some users take this doubling calculation for establishing the charging voltage and the discharge cut off voltage for the battery string. If it were true that all such batteries were identical, this specification methodology would be valid. Unfortunately, this is

almost never the case. In the normal production of batteries there exist normal process variations such that the occurrence of a selection of two identical batteries is extremely rare.

The more likely situation follows.

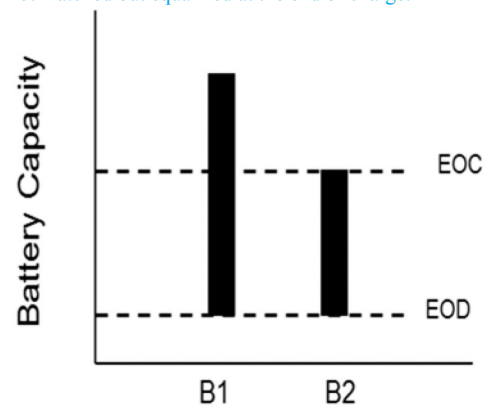


Capacity of $B1 = B2$ and pair not equalized
(a)



Capacity of $B1 > B2$ and pair equalized at EOC voltage
(b)

Figures 4a and 4b. Representations of the cases (a) where the battery capacities are equal but unequalized and (b) where the battery capacities are not matched but equalized at the end of charge.



Capacity of $B1 > B2$ and pair equalized at EOD voltage
(c)

Figures 4c and 4d. Representations of the cases (c) where the battery capacities are not matched but equalized at the end of discharge and (d) where the battery capacities are not matched and they are unequalized.