PITFALLS IN USING LONG STRINGS OF SERIES-CONNECTED LEAD-ACID BATTERY CELLS

Philip C. Symons, Ph.D.

Symons/EECI, Morgan Hill, CA

ABSTRACT

There are a number of dangers inherent in over-charging or over-discharging lead-acid battery cells, as is relatively well known. What are less well known than these dangers represent problems that can result from charging or discharging long series-connected strings of lead-acid cells. These problems can emerge in both standby and cycling applications, although they are more likely to become apparent in cycling applications. The problems arise because not all cells are made equal, and even if cells appear equal at the beginning of life, the performances of individual cells can deteriorate at quite different rates even when they are in a long series string. The performance measures that are of importance in this regard are the amp-hour capacity and the columbic efficiency of individual cells. We will show that it is possible to have one or more cells of a multi-cell string either over-discharged or over-charged during normal use. The inevitable conclusion from this analysis is that without adequate controls, a few cells of a long string of series-connected cells could be permanently damaged during normal standby or cycling operations, so that the battery will not perform to specification for its expected lifetime. Moreover, it is also possible that facility damage could result from cells being over-discharged or over-charged.

INTRODUCTION

For standby or cycling applications in which large power capabilities are required, the economics of DC cabling and of power conversion systems dictate that long strings of battery cells be placed in series. Most of the high-power installations at the present time utilize flooded or valve regulated lead-acid battery cells. The energy capacity requirements of these “high power” applications may also require that a number of lead-acid battery strings be installed in parallel, but each string must have a voltage consistent with good design for the balance of the power system. There are of course inherent dangers to personnel that are associated with battery strings at lethal voltages, and there are many questions that need to be raised and answered with regard to personnel safety in the design of power systems with long strings of battery cells. Part of the consideration of safety revolves around grounding practices for these long strings. However, except for a brief discussion in relation to ground faults, these safety issues are not going to be addressed in the following paper. Rather, the focus of the current publication will be performance issues related to utilizing long-strings of lead-acid battery cells.

It is well known that there are a number of dangers inherent in over-charging or over-discharging lead-acid battery cells. These dangers can be realized in lead-acid cells used in both standby or cycling applications. The dangers of over-discharge include permanent capacity loss and ultimately cell reversal. If a VRLA cell is over-charged, then this can lead to thermal runaway also with accompanying permanent damage. Another danger of overcharging VRLAs is excessive water loss, which can lead to capacity degradation and to “dry-out”. Observations in the past have indicated that the permanent damage from over-discharge or over-charge has included, in a few rare cases, breaching of the cell case and expulsion of electrolyte from the cell. The latter can in turn sometimes lead to damage to near-by equipment and facilities. Even in flooded cells, in which some over-charge is sometimes necessary to eliminate the electrolyte stratification that can otherwise develop in cycling situations, too much over-charge will lead to excessive water loss with a concomitant need for extra watering. If the extra watering is not performed, permanent cell damage can again result. Less dramatic effects are the more frequent impact of over-discharge and over-charge, however, the most important of which is a permanent loss of performance. This loss of performance is usually recorded as a sharp decrease in deliverable capacity of the cell.

What are less well known than the dangers cited above are the problems that can result from charging or discharging long series-connected strings of lead-acid cells. Again, these problems can emerge in both standby and cycling applications, although they are more likely to become apparent in cycling applications. These problems arise because not all cells are made equal, and even if they appear equal at the beginning of life, their performances can deteriorate at quite different rates. The performance measures that are of importance in this regard are the amp-hour capacity and the columbic efficiency of individual cells. The problems of the inequalities in capacity and differences in coulombic efficiency among cells in long-strings can be exacerbated by ground faults, the effect of which can accumulate over time and yet may pass unnoticed.

We will show in this paper that it is possible to have one or more cells of a multi-cell string either over-discharged or over-charged during normal use. This situation can be worsened if they are uncorrected ground faults. The inevitable conclusion from this analysis is that without adequate controls, a few cells of a long string of series-connected cells could be permanently damaged during normal standby or cycling operations, so that the battery will not perform to specification for its expected lifetime. Moreover, it is also possible that facility damage could result from cells being over-discharged or over-charged.

DISCHARGE OF MULTI-CELL STRINGS OF LEAD ACID BATTERIES

As stated earlier, all cells are not manufactured identically so the capacities of individual cells will be distributed around an average. Even early in life, it is possible for a few cells in a long string to have significantly less capacity than the average. The impact of this can be estimated by considering a single string battery system as shown in Figure 1, which comprises N cells in series.

Suppose the string is being discharged at a rate such that the expected cell voltage is 1.8V/cell at the depth of discharge (DOD) currently in effect and that the discharge cut-off voltage has been set for 1.75V/cell. If there are 50 cells in the string, and one of the cells has so much less capacity than the rest that its voltage is zero at this point in the discharge, then the rest of the cells could have an average voltage of 1.786V (1.75 x 50 / 49 = 1.7857) and the discharge cut-off would not quite be reached. Clearly, the one cell with discharge current being forced through it with the voltage at zero could quite likely be damaged. This situation would probably not be detected except by precise measurement and trending of the string voltage. Of course, if the number of cells in the string is greater, there is a greater probability that there will be cells with lower capacities than the rest. Thus, for longer cell strings, there is a consequently greater chance that some cells will be overdischarged or that an individual cell will be greatly overdischarged. By making measurements of the string voltage only, it is clearly more difficult to detect cells that are being overdischarged. In fact, observations on a very long string (2000V) showed that the degree of overdischarge in one of the cells was so great that the electrolyte in it was heated almost to boiling. That particular cell was ruined, but luckily there was no damage to the battery facility.

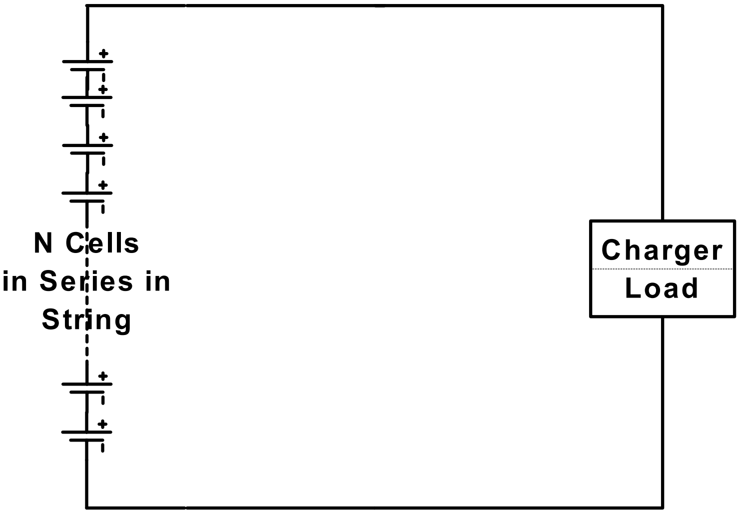

Figure 1: Single string battery system

As cells in long strings are deeply cycled, the distribution of the capacity will increase, thus increasing the likelihood of overdischarge, as now discussed. The increase in the distribution of capacity occurs because the degradation of capacity of a lead-acid cell increases with increasing DOD. It is sometimes said that, in cycling, the number of amp-hours that can be removed from a cell is a more- or less fixed amount. However, measurements of cycle life at various depths of discharge indicate that this piece of conventional wisdom is incorrect. In fact, the number of amp-hours that can be removed over life while still delivering a voltage that is acceptable to the user is significantly less at deeper depths of discharge than when the cells are cycled to a shallow depth. The exact relationship between cycle life and DOD depends on battery type, but in general terms, almost twice the amp-hours can be removed at 50% DOD as compared to the amount at 100% DOD, or, stated differently, one can get 4 times the number of cycles at 50% DOD as compared to the number at 100% DOD.

In a long series string of the type shown in Figure 1, cells with a capacity that is significantly lower than the average will be cycled to a greater DOD than other cells in the string. This will occur because in most cases, the end of discharge will be signaled by some overall measure of battery performance, such as string voltage, so that discharge current will be forced through the cells with smaller capacity by virtue of the higher performance capability of the other cells in series with the weak cells.

The consequence of the relationship between amp-hours that can removed and DOD is that the capacity of the cells with lower than average capacity will be degraded even further as compared to average cells. Thus, with cycling, the probability that the weak cells will be overdischarged will increase. This same argument applies to batteries used for cycling or standby service, of course, although it is likely that the problem will be more prominent in batteries used in cycling service.

One of the major pitfalls, therefore, of the use of long strings of lead-acid cells, without adequate monitoring of cell performance, is that some cells might be severely overdischarged. The probability that this will occur will increase as the battery is used. Since overdischarge can lead to excessive heating, cells subjected to this abuse can be severely damaged, and there is a possibility that facility damage can also result.

CHARGING OF MULTI-CELL STRINGS OF LEAD ACID BATTERIES

Referring again to Figure 1, it’s obvious that, just as in discharge, charge current necessarily passes through all the cells in the string. Additionally, if current is regulated (during finish charge or float) on the basis of the string voltage, then it is the average of the voltages of all the cells that will be used for regulation. Although this may seem self-evident, it is important to note since it can have a significant impact on the individual cells that are performing differently from the average.

In the case of charge, the performance measure that is most important is the ratio of the amp-hour capacity actually accumulated in the cell over a specific period of time to the integral of the charge current with time in that same period. This is the coulombic efficiency exhibited by the cell during charge. The coulombic efficiency in discharge is defined similarly to that in charge. Of course, the coulombic efficiency varies with the state of charge of the cell. The coulombic efficiency is close to 100% (but not identically so) at low to moderate states of charge and relatively low charge currents, and is almost identically zero when the cell is fully charged and is at the end of a finish charge or is being floated. When cells are being charged at relatively low charge currents at nearly a full state of charge, say more than 90% state of charge, the coulombic efficiency will be intermediate between a rather high and a rather low value. The discharge coulombic efficiency, while higher than in charge, will also not be identically 100%, but unlike in charge, it will be rather high at a low DOD and very close to 100% at high DOD. It is very likely that cells that exhibit a low coulombic efficiency over the entire charge period will also have a low coulombic efficiency in discharge.

The problem with long strings of cells is that there is a strong likelihood that different cells will have different coulombic efficiencies, and that within the string, there could be cells which have rather low or rather high coulombic efficiencies compared to the norm. The way in which this pitfall will exhibit itself will be quite different for flooded cells versus VRLAs.

In order to accommodate the variation in coulombic efficiency among the cells of a long string, and to ensure that all cells are recharged adequately after a discharge, enough current will have to be passed after completion of a bulk charge, or during float, to take care of the cell with the lowest coulombic efficiency. Only in this way can it be assured that the string will perform as expected during the next discharge, because cells with lower coulombic efficiency accumulated charge more slowly than the average. However, in doing this, it means that cells that had a higher coulombic efficiency during most of the charge must now be forced to operate at very low coulombic efficiency. The net result of the all this is increased water loss in all the cells, and a lower coulombic efficiency for the entire battery system. In addition, monitoring should be performed to ensure an adequate discharge capacity will be attainable.

In long strings of VRLAs, the problem with variation of coulombic efficiency among cells will show up in a quite different way. Firstly, it should be pointed out that the overall (charge/discharge) coulombic efficiency of VRLAs is much closer to 100% than that of flooded cells. Secondly, although the coulombic efficiency when a cell is fully charged is zero (or close to it) the current that can be passed under this condition, being limited by the oxygen recombination reaction, is much smaller than in the case of a flooded cell. Moreover, the rate of the recombination reaction for a given applied voltage is quite variable among VRLA cells, particularly early in life. These characteristics of VRLAs means that, in a long string, the voltage of a cell with a low rate of recombination and a high coulombic efficiency will be higher, for a given charge current, than the average of the other cells in the string. Since, without other monitoring, the current flowing in the string will be dependent on the average of the characteristics of the cells in the string, it means that some of the VRLA cells in the long string could be charged inadequately and others could be overcharged. The cells that are charged inadequately will then be overdischarged during a long discharge, and may, over time, have their capacity degraded, as discussed in the previous section. The cells that are overcharged may have excessive water loss and could possibly dry out. It is also possible that cells being overcharged could get into a thermal runaway condition, since the current being passed in the string is dependent of the average of the characteristics of the cells in the string.

Therefore, since all cells are not created equal, charging of long strings of either flooded or valve regulated lead-acid cells requires adequate monitoring otherwise the user may experience a higher in-service degradation of performance than with short strings of cells

GROUND FAULTS IN MULTI-CELL STRINGS OF LEAD ACID BATTERIES

In long strings of battery cells, ground faults can exacerbate the problems that occur with discharging and charging discussed above, and the higher voltage of long strings can make this a more a more difficult issue than it is for short strings. Before addressing the performance issue and ground faults, we want to briefly address personnel safety and grounding.

In Figure 2, we show a schematic representation of two ground faults in ungrounded battery system. Note that the ground faults are represented as resistances to ground from the battery. If the battery system in question is ungrounded (operated in an electrically floating condition) then the personnel safety issue is quite different from that with a battery that is grounded at either its positive or negative terminal. In the case of an ungrounded battery, which for many designers is the preferred situation for high voltage batteries, a ground fault, as can be seen from Figure 2, introduces a safety hazard that is not present before the ground fault occurs, since the fault completes a path to ground if someone touches any live component of the battery. If the resistance through the fault is low enough, the magnitude of the current that could flow could be lethal for maintenance personnel. For this reason, inclusion of ground fault detection systems represents good design practice for ungrounded, high-voltage batteries. With a grounded battery, the danger of electrocution upon touching a live part exists even without a ground fault, and maintenance procedures must be established and adhered to accordingly. However, because of the impact that ground faults can have on performance, inclusion of ground fault detection equipment is probably desirable even if not mandated from the viewpoint of personnel safety, as now discussed.

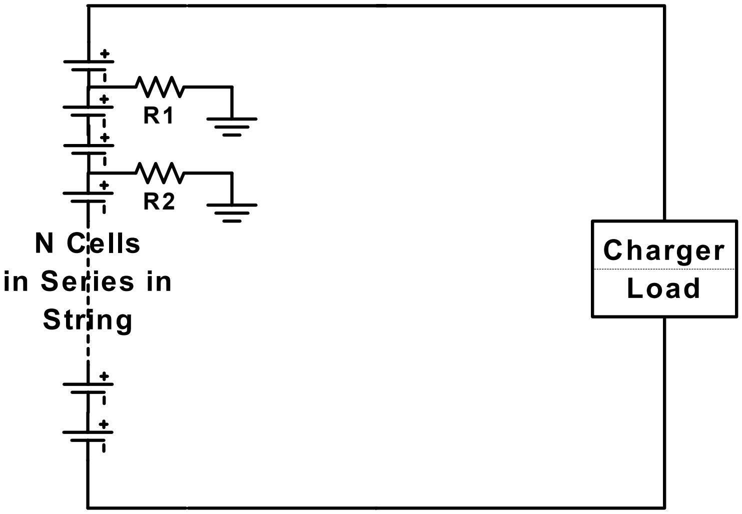

Figure 2: Representation of Ground Faults in Single Long, Ungrounded String of Battery Cells

In the case of a grounded battery, only one ground fault is required to cause a performance problem, the results of which can be inferred by analogy with the ungrounded situation.

The impact of ground faults and performance in an ungrounded battery can be conjectured by referring to Figure 2. It can be seen that the two ground faults represent an alternative path, through resistances R and R2, for discharge current to flow. This path for discharge current represents another mechanism by which particular cells in a long string can be self discharged, and thereby have an overall coulombic efficiency which is lower than cells which are not subjected to the ground faults. The ground fault path also represents a mechanism whereby the cells between the two faults will show a lower amp-hour capacity capability than other cells, so that in a deep discharge, there could become overdischarged, as discussed in the section discharge above. Since the current flows in the ground faults all the time, the effect is cumulative, and ground faults, if undetected and uncorrected, can have a quite deleterious effect on performance.

SUMMARY CONCLUSION

We believe we have shown that there are some very real pitfalls for designers contemplating the use of long battery strings in both cycling and standby applications. In order to avoid these pitfalls, more monitoring than usually considered for short strings should be put into place. Careful consideration needs to be given to the type of monitoring to be used, including consideration of the pitfalls that may beset these long strings.