AGING FACTORS IN BATTERY SIZING – PRUDENT ENGINEERING OR WASTE OF EFFORT?

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ABSTRACT

Battery capability declines with age. While many would like to believe that the manufacturers' published ratings can be supplied by their batteries right up to the end of life, this is simply not the case. To allow for this, IEEE standards for battery sizing recommend that compensation for aging be included in the sizing calculation, in the form of an aging factor. Typically, this involves increasing the required capacity by 25%. Of course, this also means that battery cost, size and weight are increased to a similar degree.

This paper demonstrates that, for applications involving high rate, short duration loads, the use of an aging factor is critical to achieving full battery life expectancy. For loads of longer duration, the aging factor is also important if the full duty cycle time is to be supported throughout life. It will be shown, however, that application of the aging factor to the exclusion of other considerations can sometimes be detrimental to system reliability. This is particularly the case in telecom systems where battery space is limited.

INTRODUCTION TO AGING FACTORS

Lead-acid batteries exhibit a characteristic pattern of capacity availability through life, as illustrated in Figure 1. These batteries actually spend half their lives or more above 100% of their rated capacity. Eventually, however, the cumulative effects of grid corrosion cause the capacity to drop off. The capacity decays gradually down to about 80% of rated capacity, then the rate of decay increases and a cell may fail suddenly through corrosion-related mechanisms. This means that operation is relatively predictable down to the 80% point, and much less so thereafter. Thus, IEEE and other documents define the end of life of a lead-acid battery as the point at which the available capacity has fallen to 80% of rated capacity.

Figure 1 also shows the aging characteristics of nickel-cadmium batteries. In this case, the battery spends most of its life below 100% of rated capacity, and the capacity decline is more or less linear. Since there is no inflexion point to the aging line, there is no definite end-of-life point. Many Ni-Cd users are comfortable with using the same 80% end-of-life point as with lead-acid, although there is no technical reason why these batteries should not be operated to a lower capacity level.

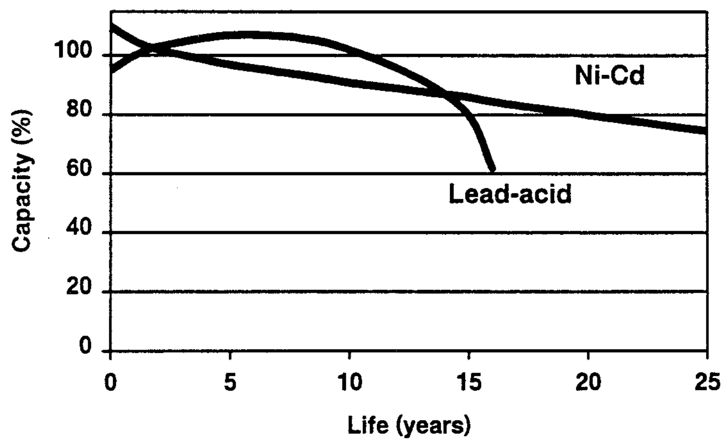

Figure 1 - Typical Life Characteristics

The IEEE publishes two recommended practices for battery sizing – IEEE 485[1] for lead-acid, and IEEE 1115[2] for nickel-cadmium. In both documents, the recommendation is to use an aging factor to compensate for the effects of capacity loss through life. For a given duty cycle, a base capacity is calculated to satisfy the load requirements, then this capacity is multiplied by the aging factor. An aging factor of 1.25 if used for lead-acid batteries, so that the installed capacity is 125% of the required size. At the end of life, when the available capacity has fallen to 80% of rated, the battery will just have sufficient capacity to perform the duty (80% of 125% equals 100%).

If 80% is chosen as the end-of-life point for a Ni-Cd battery, the same 1.25 aging factor would be used. If a lower end-of-life capacity of, say, 70% is chosen, the aging factor would be 1.43. This would result in a battery that would last longer, but of course it would also be more costly.

When used in conjunction with an appropriate testing regime, the aging factor will ensure that a stationary battery is capable of performing its full specified duty throughout its life.

UPS BATTERY SIZING – THE 12-MINUTE FALLACY

When considering the aging factor, it is important to realize that it is applied to the calculated capacity (or the number of positive plates), and not to the discharge time. In fact, derating the capacity is the same as derating the discharge current, since the two are more or less proportional for a given cell design. Thus, for a duty of, say, 100A for 15 minutes, the installed battery will be capable of supplying 125A for 15 minutes (ignoring temperature and design margin). The end of life for this battery is when it can no longer supply the specified duty of 100A (80% of rating) for 15 minutes (100% of time). This is very different from an end-of-life definition of 100% of current for 80% of time, even though both definitions seem to relate to 80% capacity in ampere hour terms. The difference is in the battery efficiency as it relates to discharge time.

A full discussion on this issue, and its impact on battery testing, was covered in a previous paper[3]. For this paper, we will concentrate on the influence that battery efficiency has on sizing calculations. Figure 2 shows a performance curve for a typical US-manufactured UPS battery design, expressed in kW/positive plate on discharge to 1.67V/cell. The curve shows that the capacity that can be discharged from this design at the 15-minute rate is 0.070kWh/positive plate. For a 12-minute discharge, although the discharge rate is some 7% higher, the available capacity of 0.060kWh/positive plate is actually 14% lower. This is because the battery is less efficient at the higher rate of discharge. Furthermore, this differential in efficiency will hold more or less true for both new and aged batteries.

This illustrates a fundamental flaw in the sizing of batteries for many UPS systems. It is quite common to size these batteries for 15 minutes at the full inverter load, with no aging factor, and to say that the battery is at the end of life when it can no longer support the full inverter load for 12 minutes. At this point, however, we have seen that nearly three-quarters of the

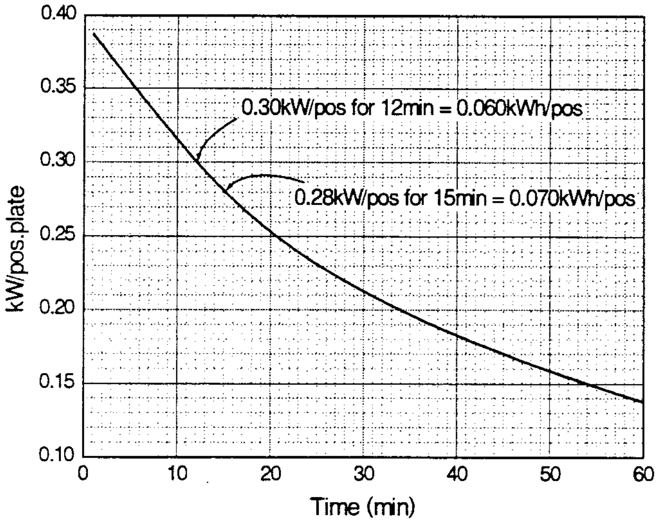

Figure 2 - Performance of Typical UPS Battery, kW/Positive Plate to 1.67V/cell

'degradation' that has occurred is actually related to efficiency losses as the discharge time becomes shorter. The actual capability of 0.28kW/positve for 12 minutes (12 minutes at the 15-minute rate) is over 93% of the 'as-new' rating of 0.30kW/positive. In this case, just 7% degradation in the battery's capability gives rise to a 20% shortfall in run time.

UPS Sizing Example

The data in Figure 2 can be used in a practical sizing example. In this case, a 400kVA UPS battery will be sized, assuming 92.5% inverter efficiency and a 0.8 power factor. The battery comprises 180 cells, discharging to 1.67V/cell. The load on the battery is $400 \times 0.8 \div 0.925 = 346$kW. For a 180-cell battery, this works out to 1.92kW/cell.

It will be assumed that the minimum acceptable battery performance is 12 minutes at full load, so this represents the end-of-life condition. The battery size is calculated three ways:

1. **12-minute battery with no allowance for aging**

   1.92kW/cell ÷ 0.30kW/pos. plate = 6.40 positive plates

2. **'Standard' 15-minute battery** (such that the end of life is at 80% of the nominal run time)

   1.92kW/cell ÷ 0.28kW/pos. plate = 6.86 positive plates

3. **12-minute battery with a 1.25 aging factor** (in accordance with IEEE recommendations)

   6.40 positive plates (from [1] above) × 1.25 = 8.00 positive plates

It can be seen from this example, with this particular cell design, that the 'standard' 15-minute UPS battery, replaced at 12 minutes of run time, includes an aging factor of just 1.07. **This is totally inadequate and will not allow the full battery lifetime to be achieved.** It is the author's opinion that this practice routinely results in 10-year UPS batteries being replaced after just 6-8 years, depending on design.

Unfortunately, users cannot rely on UPS vendors to rectify this situation. The UPS market is extremely competitive, and has been made so because these machines are frequently seen as commodity items, with the lowest bidder winning the business. The only way to ensure that an adequately sized battery is supplied is for the end user to specify the sizing parameters, especially the aging factor.

PRUDENT ENGINEERING

There is a certain school of thought that batteries can be conservatively sized using an approach of 'think of a load, then double it.' This lumped factor is then assumed to take care of battery aging, low temperature operation, load growth, and the effects of a recent discharge. Indeed, in most cases, this is a perfectly adequate approach. However, if the application involves a high rate of discharge, and the philosophy is 'think of a *time*, then double it,' this can be a dangerous approach.

In the previous example, the correctly sized battery (#3) has 8 positive plates. For the overall load of 1.92kW/cell, this works out to 0.24kW/positive plate. This corresponds to a run time of about 23 minutes, or almost double the 12-minute requirement. This means that, in this case, a sizing philosophy of doubling the run time only just accounts for the correct compensation for aging, and leaves no room for low temperature operation or other design margin.

The safest way to account correctly for all eventualities in sizing a battery for short duration loads is to follow the recommendations of IEEE 485 and 1115. In this respect, the application of an aging factor represents a prudent engineering approach. As the load duration increases, variations in battery efficiency become much smaller, and this improves the viability of other sizing methods. Unless all the sizing parameters are completely understood, however, the IEEE recommended practices remain the most prudent way to calculate the correct battery size.

WASTE OF EFFORT?

Having established that the correct application of an aging factor is the safest way to ensure that the specified duty cycle can be supported for the full life expectancy of the battery, it might seem odd to know that there are circumstances in which the application of an aging factor can actually be detrimental to system reliability. Yet this can indeed be the case when the available battery space is severely limited.

Consider the case of telephone company outside plant. Cabinets have limited space for batteries, and there is a frequent need to support higher power drains and/or longer backup times. This can create a particular problem for system engineers, who must meet mandatory reserve times while also allowing for the effects of battery aging. The situation can be made even worse if there is a need to plan for natural disasters, such as hurricanes, with even more reserve time. It is not unusual in these circumstances to favor battery manufacturers who can fit more capacity into the same space.

Sometimes manufacturers are able to achieve volume savings by employing novel assembly techniques—by redesigning intercell connectors within modules to save head space, for example. More often, though, such savings are the result of using thinner plates, so that the reduction in battery volume is accompanied by a reduction in battery life. Worse, these shorter-life batteries are frequently less reliable, and their operation is marred by premature failures of individual cells. Even one cell failing during a discharge can have a dramatic effect, as can be seen in Figure 3. The graph shows the voltage behavior of an aged 48-volt VRLA battery during a discharge at the 8-hour rate. The dotted curve shows the behavior of the single best cell (multiplied by 24 to show the effect at the battery level). If the string had comprised 24 identical copies of this cell, the overall capacity would have been about 85%.

In the actual string, however, one cell failed at just over 240 minutes. Its voltage went from 1.80V to –0.44V in just 15 minutes, and, coupled with the normal voltage drop of the remaining cells, this caused the overall battery voltage to drop more than 2.5V in the same period. This cell actually recovered to –0.31V and remained stable at that level. Additional cells started to drop out after 300 minutes, resulting in the battery dropping below the 42.0V minimum at about 305 minutes, or 64% of the nominal test time of 480 minutes.

The point here is that the battery's potential capability, judging by its best cell, was reduced by about 25% because of individual cell failures. Moreover, these failures were premature within the overall context of a shorter life for a thinner-plate product. In fact, the test result is about the same as would have been achieved at the end of life from a higher quality battery **without the use of an aging factor**, and that end of life would be more distant in terms of years in service.

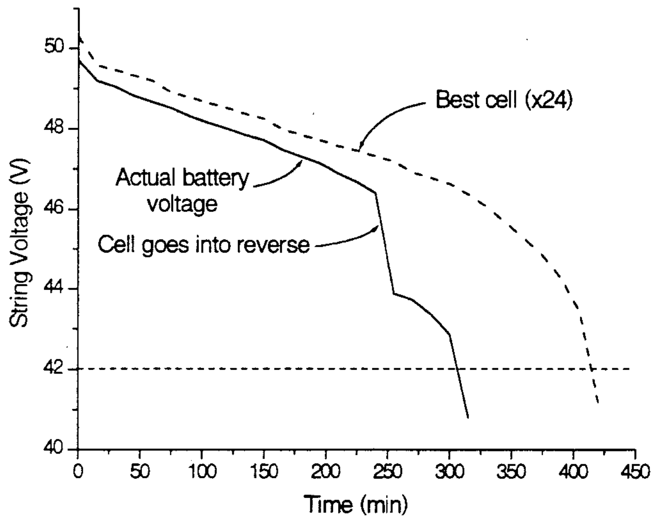

Figure 3 - Battery test results

Example

To put some numbers to this scenario, let us assume that a high quality battery is capable of giving 10 years of life under certain operating conditions, while a lower quality battery gives just 7 years. For this application, the 10-year battery can be configured for the available space with 100Ah of rated capacity, while 125Ah can be fitted for the 7-year battery. The discharge current is 12.5A and low operating temperature is not a factor.

For the 7-year battery, using the test data above, the best cell was at 85%, and so we will say that the battery age is about 6.5 years (the 80% end of life mark would be reached in 7 years). The load current of 12.5A represents approximately the 10-hour rate for this 125Ah battery. Taking the same 64% test result, we would expect this battery to support the load for about 6.4 hours after 6.5 years.

Assuming the 10-year battery shows much less cell-to-cell variability, the full string will be at 80% of capability after 10 years. In this case, the 12.5A load current is the 8-hour rate, so this battery will support the load for 80% of 8 hours, or 6.4 hours. This is actually the same run time that was achieved with the higher capacity battery, but with a major difference—the smaller (in capacity), higher quality battery could give better than 6.4 hours for 10 years, while the larger, lower quality battery could only last for 6.5 years.

There are other factors to be considered also. One of the ways adopted in achieving higher energy density with VRLA batteries is to opt for large, 12-volt modules. Depending on the physical configuration, these units may have a rather low surface area to volume ration, resulting in poor thermal management. With the lower internal resistance that comes with using thinner plates, this is just asking for trouble, in the form of thermal runaway.

This is indeed a case where opting for a higher battery capacity, to the exclusion of all else, results in a net loss to the system.

CONCLUSIONS

We have seen that the application of an aging factor is essential to achieving full battery life expectancy in high-rate applications. An aging factor is also essential if the full run time is to be supported at the end of battery life, whatever the duration of the duty cycle happens to be. However, as with other aspects of battery engineering, it is important to take a holistic view of battery sizing, and to apply margins and aging factors with a full knowledge of all the implications. Insisting on the highest possible initial capacity, regardless of other concerns, can lead the user into a more difficult situation than might be expected.

REFERENCES

[1] IEEE Std. 485-1997, "*IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications*"

[2] IEEE Std. 1115-1992, "*IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications*"

[3] McDowall, J, "*Misleading Results Using IEEE Battery Testing Procedures*," Proceedings of BATTCON99, Boca Raton, FL, April 26-28, 1999