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Valve-regulated lead/acid battery designs and charging strategies —are they linked?

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Abstract

Charging algorithms are often closely tailored to or are specified by particular applications, e.g., standby, engine start, traction, etc. When valve-regulated lead/acid (VRLA) batteries are put into these applications, the battery must fit the charging program, regardless of its design. Design principles for VRLA batteries that relate to charging in general are presented and discussed. This is followed by a discussion of the 'VRLA paradox'—a design requirement for the proper functioning of these batteries, but one that makes charging considerably more difficult than for similar flooded lead/acid batteries. Thermal effects as they relate to battery design and charging are explored, along with the impact of the conditions of the applications. Charging strategies that are best suited to VRLA batteries are examined and recommendations are put forward for both float and cyclic duties; in both cases these recommended approaches are considerably more aggressive than those currently in popular usage. In cyclic charging, the critical role of the charge termination method is explored. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: VRLA design; Float charging; Cyclic charging; Thermal effects

1. Introduction

Valve-regulated lead/acid (VRLA) batteries have been adopted into a wide variety of applications previously served by either flooded lead/acid or nickel/cadmium batteries; in addition, their unique properties have facilitated the creation of new slants on old markets such as the implementation of distributed power in the telecommunications industry. VRLA batteries are generally very robust in their design and performance, but the area of battery charging is one that has been responsible for premature failures of VRLAs where the battery is perfectly healthy but fails due to improper charging. Unlike flooded lead/acid batteries, for which both float and cyclic charging are relatively well understood and defined, VRLAs have suffered from an inherent non-uniformity due to what may be called the 'VRLA paradox', or 'VRLA knife edge'. This is the design condition upon which VRLA technology is based whereby each cell operates in an 'almost starved/almost flooded' mode. What is meant by this is that the VRLA design employs just enough electrolyte to provide the needed discharge capacity and, at the same time, a small enough amount so that there is sufficient void space to accommodate the oxygen recombination process. In order to attempt to make cells as uniform as possible in the manufacturing process, electrolyte amounts are accurately metered into cell/battery elements in the filling operation. Nevertheless, unavoidable variations in upstream materials such as grid, paste and separator ensure that these precisely reproducible amounts of electrolyte go into plate stacks with variable amounts of void space within fixed case dimensions. This results in filled and formed cells having slightly different void volumes in their finished states. When these cells, as batteries, go into charge/discharge cyclic or float operation, they will each behave slightly differently during the charging process due to small differences in the available void volume and differences cell-to-cell in the compressed separator structure. These two factors result in vastly different performances cell-to-cell in a battery under charging conditions, largely due to amplified differences in the creation of gas channels between the plates for oxygen recombination. The formation of gas channels depends upon the total void space available as well as the ability of the compressed separator structure to accommodate fluid move-

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ment. These two factors, as well as others such as the overall electrolyte distribution between the plates and the separator, result in significant differences cell-to-cell in the balance between oxygen recombination and hydrogen evolution on the negative plates. It is these processes that control the cell charge voltages. In flooded cells, where oxygen recombination is excluded, the cell-to-cell variability is not such a large factor. In VRLA products this amplified variability, largely due to the oxygen-recombination process, is the 'knife edge' referred to above. The necessity for this delicately-balanced condition is the 'VRLA paradox'. This balanced state is required for the proper functioning of VRLA cells and batteries, but it creates a difficult situation in terms of charging in that the charge acceptance varies considerably cell-to-cell throughout a battery.

What can be done about this in designing VRLA products? Manufacturers control materials amounts cell-to-cell as best they can and it would be impossible to meter in variable amounts of electrolyte from one cell to another to compensate for variations in other materials. Reducing or increasing the nominal fill amount outside of that necessary to give a void volume of 5–10% can be problematic or disastrous. Underfilling results in excessive recombination (due to a high void volume) and poor filling patterns; the latter can result in high levels of grid corrosion in some areas of the cell where dilute electrolyte may be present during the formation process. Overfilling will lead to spewing of electrolyte during and after formation, followed by field performance where the oxygen recombination/hydrogen gassing balance is skewed toward gassing; in addition, acid spray and high levels of grid corrosion can occur. A more effective approach is to control the charging algorithm applied to a VRLA battery in a particular application to attempt to compensate for this inherent variability.

In many present applications, the above situation is aggravated by the tendency for battery manufacturers to recommend conservative charging algorithms for VRLA products, under the assumption that, because of their relatively thin grids and limited amounts of electrolyte, overcharging will cause premature failure. There is some truth in this but *undercharging* is a far greater handicap, as shown conceptually in Fig. 1. Overcharging in float and cyclic applications will certainly decrease the float or cycle life by some 10–20%, but undercharging can result in very early failure, as shown in Fig. 1. The propensity for VRLA products to be undercharged has recently been discussed by Atlung [1] for cycling duty cycles and by Berndt [2] for float conditions. In both studies, the result was a significant loss of service life. In both instances, however, the authors only considered the charge voltage or charge amount applied to the batteries and did not take into account the *rate* of charge or recharge. A central thesis of this paper is that, for both float and cyclic charging, the rate of the charging process is at least as important as the amount of charge returned. Moreover, for cyclic duty it will be proposed that the method of charge termination also has a great deal to do with the useful battery life. Finally, radically different VRLA design and charging strategies will be proposed for batteries going into cyclic duty.

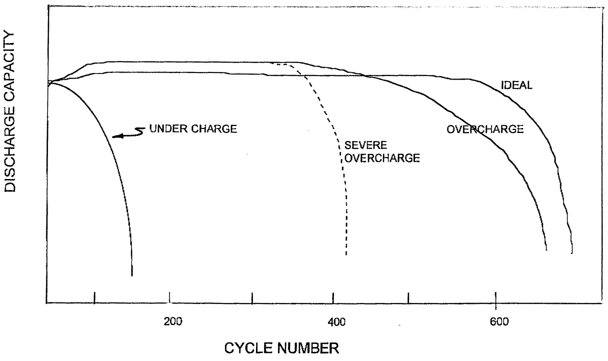

Fig. 1. Qualitative effect of charge strategy on cycle life.

2. Results and discussion

Many manufacturers of VRLA products have based their designs upon flooded lead/acid batteries that they have developed; in some cases, the same plates have been used and the only real design changes have been the replacement of the flooded battery separator with glass microfibre (AGM) or gelled electrolyte and a reduction in electrolyte volume. Also, charging principles have been based upon vast experience gained with flooded batteries and, to some extent, these have not been tailored to the special needs of VRLA products. The presence of the oxygen-recombination process not only allows for valve-regulated operation, but puts unique constraints on the charging algorithms used for both float and cyclic usage.

2.1. VRLA design principles

When flooded lead/acid batteries are charged, both the negative and positive electrodes are easily polarised and each functions more or less independently of the other due to the flooded construction; in the absence of impurities or other deleterious influences, each polarises according to its Tafel relationship with, theoretically, slopes of 80 mV per current decade for the positive and 120 mV per decade for the negative. The major overcharge reactions are oxygen evolution and grid corrosion at the positive, and hydrogen evolution at the negative. Water loss is stoichiometric and grid corrosion depends largely upon the degree of polarisation from open circuit in float operation; on cyclic duty, a 10–25% overcharge current fraction is usually sufficient to ensure full recharge following a discharge. While the electrochemistry on the two electrodes is not completely homogeneous, it is well characterised and plate polarisations cell-to-cell are uniform and largely dependent upon the applied voltage.

In VRLA cells, the positive electrode behaviour is nominally the same as in a flooded battery, at least in terms of the primary charge process and oxygen evolution on overcharge. The negative electrode, however, operates in a ‘mixed potential’ mode [1,3], where, in overcharge, some areas experience oxygen recombination and others are supporting hydrogen evolution [3]. This is largely due to the irregular separator structure and the distribution of electrolyte prior to overcharge. In the quiescent state, as well as during the primary charge processes when little or no gases are generated, it is likely that the separator is flooded, or nearly so, and thus significant oxygen recombination cannot occur once the positive goes into overcharge until the ‘pumping’ action of the gases generated at one or both of the electrodes creates gas paths through the separator. In a given cell, this will not be uniform throughout the separator, and cell-to-cell it will not occur in the same way or, probably, at the same time. Thus, every cell in a battery behaves somewhat differently on overcharge, whether it be float charging or cyclic recharge.

Hydrogen evolution will tend to polarise the negative plate to relatively high (i.e., more) voltages, following the Tafel relationship as it would in a flooded cell. Oxygen recombination, on the other hand, depolarises the negative, as the oxygen reduction potential is below the open-circuit value for the negative plate. If one or the other process dominates, it will dictate the overall plate voltage, and thus the cell voltage, as the positive-plate potential is relatively constant. As noted previously, driving the negative plate to one or the other extreme by increasing or decreasing the electrolyte amount is not a viable solution. In the highly-starved state, the negative plate is completely depolarised and this can result in incomplete recharge [1] and/or thermal runaway [4], along with a lowered nominal discharge capacity. If the cell is flooded, or almost so, it will experience high levels of gassing (both hydrogen and oxygen) and, possibly, grid corrosion. As water is ‘cooked off’, the cell will achieve a more balanced condition, but at a high price. Furthermore, with improper charging and/or usage conditions the battery can go from this desirable balanced condition to one where it is electrolyte-deficient. This will occur to some extent as a result of the basic battery design (water loss through the plastic walls and/or the vent valve) as it ages in use, but excessive overcharge will accelerate this process greatly.

The design of a VRLA battery is important in how it affects the efficiency of the oxygen recombination process, but it is not the complete solution to the ‘VRLA paradox’, particularly if a battery design is to be put into a wide variety of applications, both float and cyclic duties. Proper charging, in combination with an optimised design, will create a condition of long service life. The contribution that can be made through proper design is to create a product that has the balanced recombination/hydrogen evolution capability discussed above, as well as the ability to achieve it relatively rapidly. The role of charging is to keep the battery at a full state-of-charge by applying minimal overcharge, and thus minimal water loss and/or grid corrosion.

In terms of design, the approach that will facilitate full recharge (or maintenance of it in float conditions) with minimal overcharge is one using thin plates that are closely spaced, along with an amount of electrolyte that results in an overall void fraction that is 5–10% of the total plate stack envelope. The use of thin plates in VRLA products has largely been avoided due to a combination of manufacturing limitations and the perception of positive-plate corrosion automatically resulting in unacceptably short service life. These factors can both be avoided through a combination of using low-corrosion rate alloys and/or new grid preparation methods that employ various mixtures of casting, cold rolling and/or expanding, with the result being vastly-improved grid tensile strength and the creation of grain structures that further reduce the corrosion rates. Later, it will be seen how these thin-plate batteries can actually have enhanced float and cycle lives when combined with the proper charging algorithms. It is important to note that design alone will not achieve the goal of improved service life; in fact, if a thin-plate battery is not charged in the proper fashion it will, predictably, have a shorter lifetime than an analogous thicker-plate product. Apart from improvements in specific energy and specific power, the thin-plate approach creates the opportunity to apply charging algorithms that are not possible with more traditional designs. The key parameters in charging are fast response and minimal overcharge.

2.2. Float charging

In addition to dealing with the VRLA ‘knife edge’ that is inherent in the design of this type of battery, attempting to apply traditional float charging methods (those derived largely from experience with flooded lead/acid batteries) to achieve long service life is like ‘dancing on the head of a pin’ (Feder, private communication). When VRLA batteries are on float charge, the voltage and current are set low so that gassing and/or grid corrosion are not excessive. Most float applications use constant-voltage (CV) charging, with a polarisation of some 100–150 mV above open-circuit. The applied voltage, however, is some multiple of this depending upon the length of the cell string. How the applied float voltage is divided up between the individual cells cannot be controlled, so in many cases a bimodal distribution of cell voltages will occur, as shown in Fig. 2 [5]. Cells that are ‘almost flooded’ will attain relatively high voltages and exhibit hydrogen evolution and those that are ‘mostly starved’ will operate at lower voltages due to the depolarizing effect of the oxygen-recombination process. Those that experience depolarisation run the risk of being incompletely charged: for example,

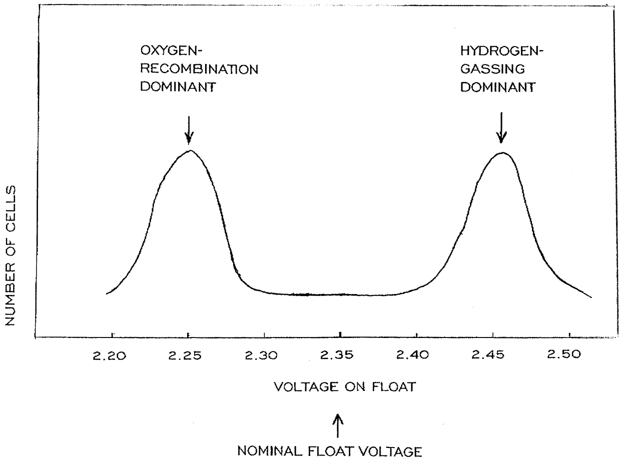

Fig. 2. Bimodal distribution of VRLA cells on float charge.

Berndt has pointed out that cells like this can have negative-plate discharge occur on float charge [2]. This bimodal distribution will tend to blur with long float times, of the order of months, but in that time negative-plate discharge can easily occur and one or more load discharges may be required, with disappointing results.

Clearly, the bimodal distribution can be shifted to the high-voltage side by increasing the nominal float voltage. This would ensure that fewer cells would be in the oxygen-recombination/negative-discharge region, but the average float current would be higher and there would be more hydrogen evolution and grid corrosion, both of which could severely shorten battery life [6]. Proper float conditions are a tremendous dilemma for VRLA technologists and users such as telecommunications and UPS system operators. The inherent uncontrolled charging condition is aggravated in some instances by systems designers putting the batteries into high-temperature environments where they are at risk of going into thermal runaway. Given all of this, it is clear that a radically new approach to float charging is necessary to facilitate the wide application of VRLA technology in this type of duty cycle.

One suggested approach is the use of a technique called 'intermittent charging', pioneered by D. Reid of Northern Telecom in the mid-1980s for telecommunications applications [7]. It is just what the name implies, a charging algorithm that is applied to a battery system only long enough, and on a periodic basis, to keep it at or above about a 95% state-of-charge. In Reid's original work, charging was performed on a telecommunications battery with several strings in parallel and was alternated so that only one string at a time would be charged. In applications where the battery would not be required to be 'on line' continuously, a preferred approach would be to charge the battery for a short period and then allow it to stand on open-circuit until the voltage would drop to a particular level indicative of, say, 95% state-of-charge, at which point it would be recharged again for a short time. For batteries with excellent self-discharge behaviour, this charging period could be as little as 1 to 2 hours per week, perhaps a bit more in high-temperature applications. Different charge algorithms can be used, either sensing voltages as described above or using a simple timed charge (so many hours per week). Intermittent charging has a number of attractive features for float duty cycles, among them the following.

- For batteries with good self-discharge behaviour and low open-circuit corrosion rates lifetimes can be extended considerably.
- Because the battery is on charge for such a small portion of the time, aggressive charging voltages can be used to ensure that all cells are fully charged; it is more like cyclic charging in a float application. For short charge periods, voltages as high as 2.60 V/cell can be used to ensure cell-to-cell charge equalisation within the battery.
- Power consumption is reduced and on-line problems such as AC ripple corrosion, normal grid corrosion and electrolyte dryout are minimised.
- With such short charge periods, thermal runaway is virtually eliminated.

This approach would not be suitable for all float applications, but it is one way of getting around the vexing problem of VRLA cell-to-cell variability on float charge. Another approach is to electronically monitor and control individual cell charge–discharge performance, as has been done by Ericsson, but this is normally very expensive. The real beauty of intermittent charging is that it allows aggressive float charging of a VRLA battery, one of the few ways to avoid having to 'dance on the head of the pin' and achieve good state-of-charge uniformity. Combined with the thin-plate design described above, it provides a very efficient package that results in rapid, efficient (i.e., low overcharge percentages) charging in order to handle frequent outages and minimise the usual aging factors of grid corrosion and dryout.

2.3. Cyclic charging

VRLA battery design certainly has an impact on performance in float applications, particularly with regard to grid corrosion and dryout, but in cyclic applications its impact is enormous; in fact, it literally determines performance in a number of areas. It is in the area of cyclic duty that the thin-plate VRLA design can yield outstanding results while avoiding the obvious failure mode of grid corrosion, particularly in concert with a proper charge algorithm. The key is the charge efficiency of a thin-plate battery compared with that of a thick-plate analogue, as shown in Fig. 3. Because of the high surface areas of the plates and the proximity of the electrolyte reservoir to the plate pore reaction sites, recharge efficiency is very high until 80–90% state-of-charge. Moreover, these same design factors

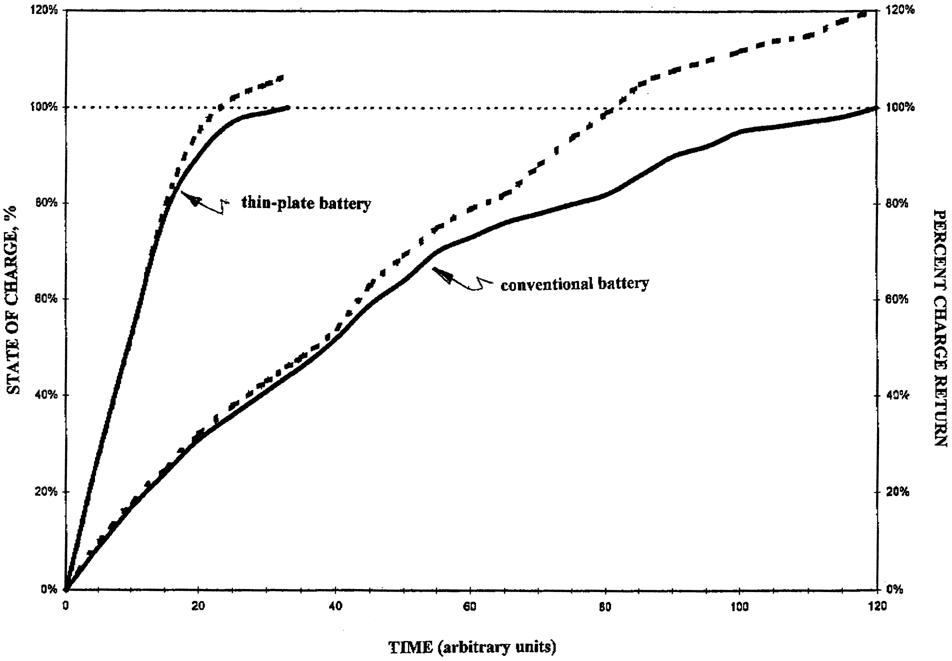

Fig. 3. Charging curves for conventional thick-plate and thin-plate VRLA batteries. Solid line is state of charge; dotted line is percent charge return.

ensure that the vast majority of the overcharge current will go into oxygen recombination (which will be almost 100% efficient) rather than hydrogen evolution and grid corrosion (which, unlike recombination, are degradative processes). The charge efficiency of a conventional thick-plate cell is lower and the thick separator layer results in some of the electrolyte having to diffuse over relatively long distances to get to the plate pores; these design features and the resultant high impedance prohibit rapid charge input and lead to relatively slow, inefficient recharges with high overcharge levels, as shown in Fig. 3.

Rapid charging with attendant high-inrush currents has become an accepted technique for realizing enhanced cycle-life performance in VRLA batteries, particularly in EV applications. This approach can be used for many other applications if a thin-plate VRLA design is employed in concert with the proper charging and charge-termination strategies. It is clear that the charging approach *not* to use is the one most commonly employed for VRLA batteries, CV charging. Unless very high voltages are used (in which case CV charging becomes a quasi-taper charge algorithm), the long ‘tail’ on the CV current-time curve ensures a long period of inefficient recharge. Constant-current charging (CC) is acceptable, but it is difficult to identify the proper charge current. If it is too low, the same overcharge inefficiency as with CV is suffered; if it is too high, substantial overcharge cannot be avoided just by the nature of the high current input. Choosing a moderate current level will work in many cases and the use of 2-step CC, a method commonly employed, will also be workable, but diminished efficiency for the primary charging process will again be encountered on the low-current step.

The best methods for charging thin-plate VRLA cells are pulsed- and taper-current charging. Pulsing is good, because it allows for rapid charge injection in a short time with minimal overcharge, all of this with high inrush currents. Taper-current charging has the same advantages, but with an entirely different approach. It is extraneous for this discussion to go into the details of these two charging methods, as they are well documented. These are not common charging techniques in VRLA technology, but as battery designs tend toward thin-plate configurations (as is likely) they will become the methods of choice for most applications. The major drawback to fast charging, of course, is the requirement for high current levels, and, thus, more substantial chargers. This issue will no doubt be resolved through the development of higher-power solid-state devices that is now under way. The key to rapid, high-current charging is in providing sufficient current to ‘overpower’ the recombination process, which becomes more and more dominant as a battery ages. It is also important with thin-plate designs, where high surface areas and small plate spacings promote higher efficiency.

2.4. Charge termination considerations

A great deal of effort usually goes into the development of chargers for a manufacturer’s VRLA product line; in fact, most manufacturers either specify or provide specialised chargers that are designed for their batteries. When it comes to the charge termination strategy to be used, there is often recourse to the old standbys of timed charge or a fixed percentage of overcharge, some 10–25%, depending upon the particular technology. More sophisti-

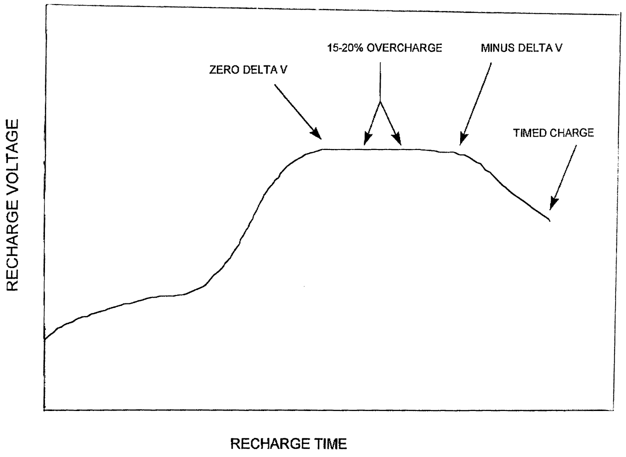

Fig. 4. Various charge termination methods as they relate to charge time.

cated designers, particularly those working with thin-plate VRLA products, may mimic the nickel/cadmium approach of using the 'minus delta V' point on the recharge voltage/time curve, as shown in Fig. 4. All of these techniques have significant disadvantages when combined with fast-charge algorithms. Timed charging will necessarily involve significant overcharge, as the time must be chosen to accommodate changes in the charge–discharge periods that vary as a battery ages. The use of a fixed percentage of overcharge is useful early in battery life, as it almost certainly ensures a full recharge. Nevertheless, as the battery ages and more overcharge current goes into oxygen recombination, a point may be reached where even a 25–30% overcharge level is insufficient to compensate for the required recombination current: the battery's discharge capacity will then experience a 'walkdown' in capacity just as if it were not being provided with sufficient overcharge. The 'minus delta V' approach is successful in nickel/cadmium batteries (often in combination with temperature sensing) because the recombination 'hump' in the voltage-time charge curve where the cell transitions from predominantly hydrogen gassing to a mix of gassing and recombination is well-defined and occurs rapidly. In VRLA batteries, the hump may take a significant time to occur or may not occur at all. Thus, this termination strategy can also involve large levels of overcharge that will shorten life.

The 'zero delta V' sense technique is also used for nickel/cadmium and nickel/metal hydride batteries and it is well suited to thin-plate VRLA batteries that are fast charged. With conventional thick-plate VRLA (or flooded) batteries, this method would be avoided, because at this point there is considerable unconverted active material in the plates, i.e., the battery is not completely recharged. This is usually the approximate area on the voltage-time curve where a two-step charge method will go from the high charge rate to a low one to complete recharge. Because of high charge efficiency of thin-plate cells, this point is adequate to ensure full recharge, without significant overcharge. In some cases, a small (< 5%) fraction of the nominal discharge capacity may be lost, but not in a progressive fashion that leads to capacity walkdown. The number of cycles obtained will actually be greater than with conventional charging methods because grid corrosion and/or dryout are minimised due to the small fraction of overcharge that does not go into oxygen recombination. Most sensing techniques for zero delta V are electronic and iterative, so the charging process is not terminated at that point, but somewhat beyond it. This results in significant overcharge, but as long as most of it goes into oxygen recombination (which it will with a thin-plate design) it is not damaging to the battery.

3. Conclusions

Clearly, VRLA design and charging strategies are linked, perhaps more so than for analogous flooded lead/acid products. This is due to the oxygen-recombination process that creates significant differences in charge acceptance cell-to-cell in a battery. This is true both in float and in cyclic charging and it is suggested that a better approach may be to charge more aggressively than has been done in the past for both VRLA and flooded batteries. On float, the technique of intermittent charging is recommended and in cyclic use, high-inrush taper current and pulsed-charging should be developed. The optimal design for VRLA batteries is a thin-plate one that, with the proper charge algorithm, can yield longer float and cycle-life values than those currently being obtained with conventional designs and charging strategies. In cyclic applications, this extended life is realised due to the protective effect of oxygen recombination in overcharge, resulting in reduced corrosion rates on a calendar basis relative to thicker-plate battery designs.

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