LOW ASPECT RATIO VRLA CELL FOR HIGH POWER AND LONG LIFE IN RACK-MOUNTED UPS APPLICATIONS

George Brilmyer and Michael Gilchrist
HighWater Innovations, LLC

Background

The UPS battery industry is well established and offers a wide range of products for all sizes of applications. In small office applications (<1500 VA) low voltage VRLA battery systems are used in integrated UPS cabinets that fit into closets and beneath desks. In huge server room applications, large UPS systems (>40,000 VA) use large racks of flooded lead-acid or VRLA batteries that operate at system voltages in excess of 400 VDC. The mid-sized UPS applications (2,000 – 5,000 VA) are much more problematic in terms of battery size. For example, many small data rooms simply have one server rack fitted with only one or two servers, with power demands below 5KVA. Using low battery bus voltages such as 12-48VDC, necessitates the design and use of large batteries or cells that are capable of outputting hundreds of amperes. This requires the use of large wires, cables and connectors. On the other hand, use of a high voltage battery bus (~200VDC) results in the use of very low capacity batteries (or cells) that are even more cumbersome in terms of wiring and are not designed for high voltage bussing. There is clearly a need for batteries (or cells) that better fit this mid-sized application.

One type of battery technology that is currently well known in the industry is spiral-wound VRLA technology. This technology has the advantages of having more uniform plate to plate compression and since the container is cylindrical, can be operated at higher pressures for optimum oxygen recombination. Known for its high power and long life, spiral-wound designs have great possibilities, but tend to have fitment and connectivity issues when used in high voltage systems.

There is a need for a spiral-wound VRLA design that offers 1) good connectivity for high voltage systems, 2) very high power for short (<15 min) demand periods, 3) longer-life and 4) a compact footprint for rack-mounted applications. Another functionality that has growing support from systems types is the ability to monitor individual cells using an automated BMS (Battery Monitoring Systems). These systems are becoming increasingly more affordable and are proving their value to the industry.

Discussion

Despite the varied application and design, conventional spiral-wound VRLA cells all have the same common feature related to their shape. They all have a high aspect ratio (Length > Diameter) and tend to have the shape of a beverage can. Accordingly, the conventional VRLA cell tends to function better if placed side-by-side. Electrical terminals for these VRLA cells tend to protrude from the top of the cells and thereby further limit the ability to interconnect cells. The terminals tend to be light gauge and are not designed for power. These high aspect ratio cells have tall grids (in the length direction) and with their limited number of grid tabs (lugs) may result in higher resistivity and more voltage losses. Attempts have been made to improve the high rate performance of these cells by employing multiple tabs on both ends of the cells but these designs have either not been accepted or cost-effective.

VRLA batteries, along with most other battery chemistries, also have an inherent drawback, which relates to the effect of temperature on charging voltage / current. Not only will the life of the battery be decreased as the operating temperature is raised, but for a given temperature there is always an optimum charging voltage (or current) for maximum performance and life. The best operating conditions place the battery and all of its cells at the identical temperature so that the charging voltage can best be controlled and optimized. For a selected charging voltage a cell operating above the average pack temperature will experience overcharge while a cell operating below the average pack temperature will be undercharged. A cell that is operating at a temperature measurably above the average battery pack temperature will only become hotter due to overcharge (and oxygen recombination) and this may eventually lead to a thermal runaway situation (constant current charging has similar scenarios). A battery pack and cell design is clearly needed that will afford better pack temperature control and cell temperature uniformity.

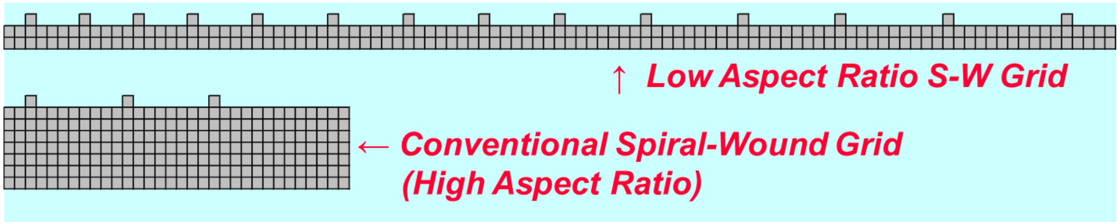
In view of the foregoing descriptions, an optional design is proposed. This design has a low aspect ratio, where the length < diameter and the cell therefore resembles a disk such as a hockey puck. The low aspect ratio cell has an open central core that is specifically designed for thermal management. Several stages of the prototype design are shown below.

Figure 1. Cell Structure

In the upper left photo (cell number 5) we show a wound cell without the cast-on-straps (COS). This particular cell has eight (8) wound laps with each lap having two tabs on the negative grid per lap and two tabs per lap on the positive grid. The photo at the upper right (cell 7) shows the structure of the cast-on-straps. Two straps collect the current from the positive tabs and two straps are used for the two sets of negative tabs. These COS were intentionally made oversize (by ~400%) to compensate for possible tab alignment issues in the winding and construction of the prototypes. We now know this was not necessary and future prototypes will make use of a smaller and lighter COS design. The bottom photo shows the prototype cell in its machined ABS case. These photos also show how the cell is wound onto a hollow core for thermal management but that will be discussed later. The multiple tabs work in concert with double straps for high power. Though the straps in these prototypes were designed to be much larger than necessary, their advantages are seen. The associated posts extend through the cover of the cell (see lower photo) and that are designed to create a unique system for cell inter-connectivity. Besides the normal advantages of a spiral-wound design, the cells shown above have more uniform compression near the core (due to the integrated large core) and multiple tabs for higher power.

A simplified comparison between the low aspect ratio grid and a conventional grid for a spiral-wound cell is shown below in figure 2. Both grids shown below have the identical geometric surface area of 386 cm^2. The low aspect ratio grid is 152cm in length, 2.54cm in height and has 16 tabs. This compares to the conventional grid that is 43cm in length, 8.9cm in height and has only 3 tabs.

Spiral-Wound Grid Comparison: LAR-VRLA Grid vs. Conventional VRLA Grid



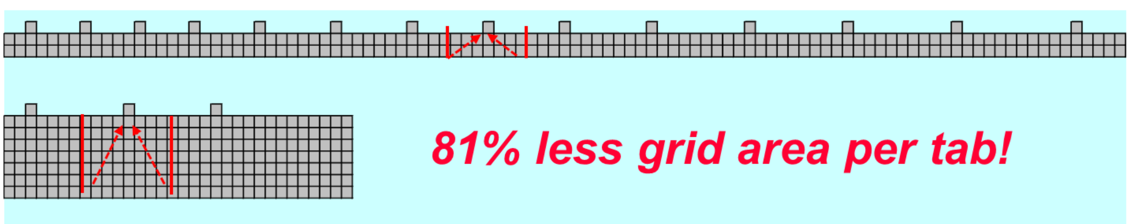
	Grid Active Area		Grid Length		# of Laps	Grid Height		# of Tabs	Avg. Area per tab	
	cm**2	Sq.In.	cm	Inches		cm	Inches		cm**2	Sq.In.
Low Aspect Ratio	386	60	152	60	8	2.5	1	16	24	3.75
Conventional Spiral	386	60	43	17.1	3	8.9	3.5	3	129	20

Figure 2. Spiral-Wound Grid Comparison: LAR-VRLA Grid vs. Conventional VRLA Grid

Referring again to Figure 2 we can see that the current path from the bottom to the top of each grid is dramatically different. In the low aspect ratio grid, the current path is only 2.5 cm while in the conventional grid design the path is almost 9 cm. This is a net reduction of 71%, which is design to improve (reduce) electrical resistance and high-rate performance.

Taking a closer look at the grids, we can compare the dramatic effect of the higher number of tabs (see figure 3) in reducing the localized voltage drops. We show that there is less grid area associated with each tab and therefore less current per tab. In the case of the low aspect ratio grid each tab has a geometric area of ~24cm^2 associated with it, while in the conventional grid, each tab has an associated ~129cm^2. This is 81% less associated grid area per tab and each tab will therefore have 81% less current flowing through it. The net result will be less Ohmic loss and higher power at high discharge rates.

Average grid area per tab comparison



	Avg. Area per tab		Net	Reduction
	cm**2	Sq.In.		
Low Aspect Ratio	24	3.75	19%	81%
Conventional Spiral	129	20	N/A	N/A

Figure 3. Average Grid Area Per Tab Comparison

The cell design itself is unique and was designed a compact stack-like structure. In Figure 4, finished cells are depicted with a twist-lock inter-cell connector design. The drawing on the left shows the top of the cell with its’ four posts (2 positive, 2 negative) protruding from the cover. These lead-alloy posts are soldered to tin-plated copper twist-lock terminals. The one-way pressure relief vent is positioned within a recessed area for protection.

Stackable Cell Design. The top of the cell is shown on the left and the bottom of the cell is shown at the right.

Per design the cell depicted in Figure 4 has a 7.6cm (3”) outer diameter, 2.5cm (1”) inner diameter and a body height of 3.8cm (1.5”).

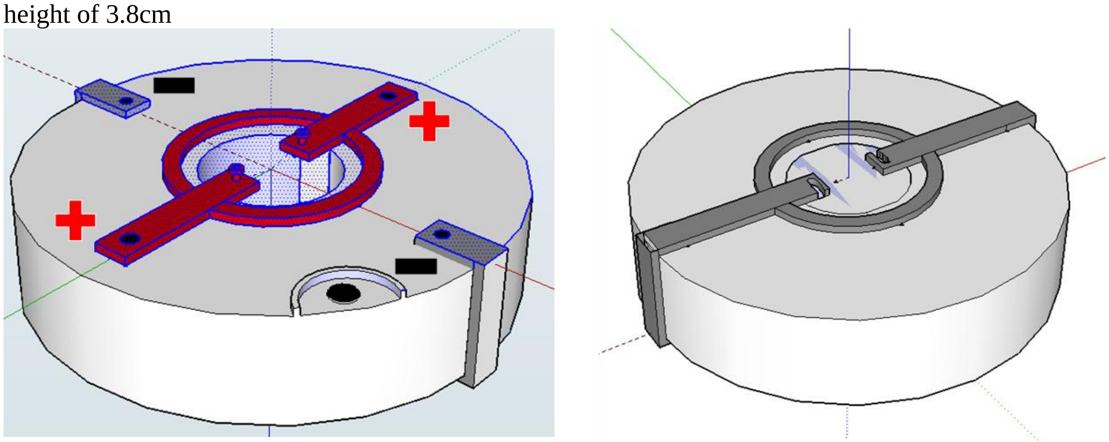


Figure 4. Stackable Cell Design

With an opposed electrode area of 252cm^2 this cell is ~6.0Ah at the 1-hour rate. The open cell core is used for cooling the cell and through more uniform winding tension, creates a cell that more effectively utilizes the material on the inner-most laps. The cell as shown will have an estimated weight of 0.45Kg.

The single cell building block gives the battery pack designer many advantages. The compact footprint enables batteries to be constructed at any voltage with varied dimensions. The single cells also afford the pack assembler the ability to test, match and balance each cell for use in battery packs. Matching can be done based on cell capacity, cell resistance, cell float voltage and other such variables. In operation, a BMS can even be used to monitor each cell in the battery pack if required.

In Figure 5 a 12-volt stack of cells is shown in both an “exploded” and “assembled” view. These stacks can be produced in any voltage necessary to fit the available space requirements.

Stackable Cells. The drawing on the left shows an exploded view of a stack of cells. The drawing on the right show these same cells stacked and interconnected.

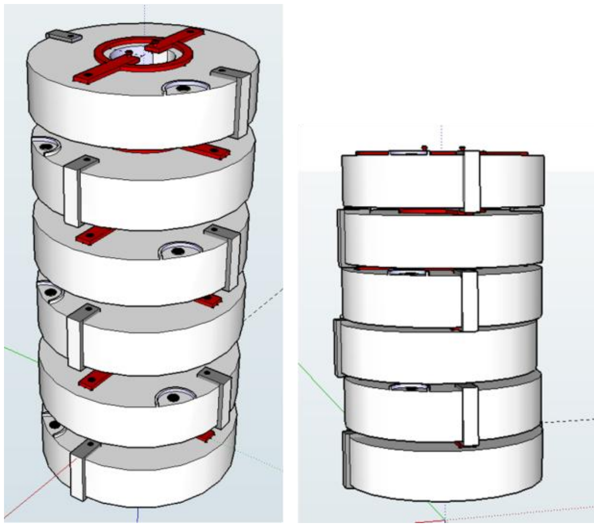


Figure 5. Stackable Cells

These low aspect ratio cells can be used to design any number of battery packs and battery systems. The packs themselves will be naturally compact and will have unique flexibility of design and fitment. Single cells can be produced in any size and used for pack assembly. Besides having high power these battery packs are designed for long life through proper thermal management. The cylindrical design and hollow core are particularly amenable to air-cooling. This will give the user the ability to place these batteries in hotter climates with the understanding that all cells will be operating under the identical temperature and conditions. Chilled air can be directed into the battery pack thus eliminating the need to cool the entire room. An example of a possible rack-mounted battery pack is shown in Figure 6. This particular 200-volt battery pack is 18” (W) x 24” (L) x 3” (H), has 96 cells (Design 1 - Table 1) and is designed to fit compactly into a conventional server rack.

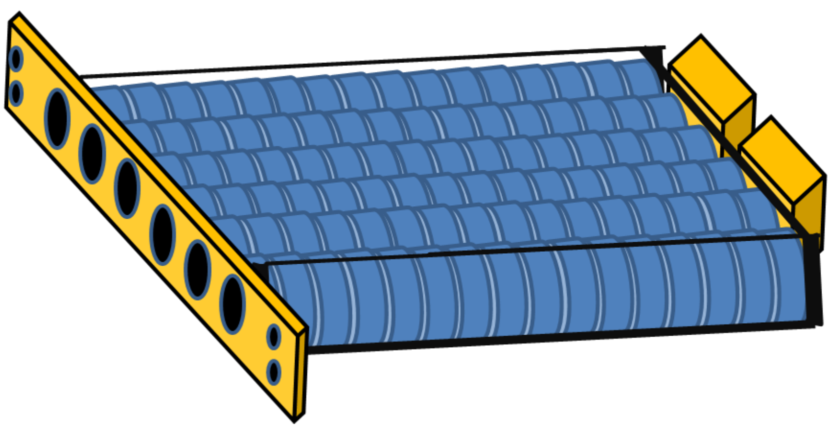


Figure 6. Rack-mounted air-cooled low aspect ratio VRLA battery pack

The capacity and performance of the low aspect ratio cell can be easily altered by increasing or decreasing the number of wound laps. Table 1 below shows design estimates for cells containing 6 or 8 wound laps.

Cell Variables	*Design 1*	*Design 2*
Capacity (c/1)	6.5 Ah	9.5Ah
Cell OD	7.6cm / 3.0”	9.9cm / 3.5”
Cell ID	2.54cm / 1.0”	2.54cm /1.0”
Body Height	3.8cm / 1.5”	3.8cm / 1.5”
Wound Laps	6	8
Opposed Plate Area	252cm2 / 39 in2	386cm2 / 60 in2
Weight	0.45Kg / 1.0#	0.68Kg / 1.5#

Table 1. Design estimates for cells containing 6 or 8 wound laps

Cell prototypes were built and assembled using grids, separators and other components that were readily available. A cell winder was constructed and the oversized cast-on-straps were designed to compensate for the anticipated variability in paste thickness (hand-pasted) and winding tension. Photos of these prototypes are shown below in Figure 7 (and in Figure 1). These cells demonstrate an optional “slide lock” terminal design that is under development. Since these particular cells were constructed using components that were not designed for this exact purpose, these cells were far from optimized. The specifications of these prototype cells are shown in Table 2.

Prototype Low Aspect Ratio Cells with “Slide-Lock” terminals. Top (left), Bottom (right).

Figure 7. Cell prototypes

Prototype cell – Actual Specifications

Cell Variables	Design 1
Capacity (c/1)	6.0 Ah
Cell OD	8.5cm / 3.35”
Cell ID	1.9cm / 0.75”
Body Height	4.7cm / 1.86”
Wound Laps	6
Opposed Plate Area	252cm2 / 39 in2
Weight	0.74kg / 1.62”

Table 2. Prototype cell – Actual Specifications

High-rate testing of these prototypes was done with the use of a slightly modified terminal design that permitted the attachment of high power cables (see Figure 8). Sensing leads were used to monitor the cell voltages during high-power testing and four cells were tested and the average data is presented below (Table 3). Short circuit current testing produced currents ranging from 900-1,000 amps.

Prototype cells fitted with terminals for high-power testing. The top of the cell is shown on the left and bottom of the cell is shown on the right.

Figure 8. Prototype cells

Run Time	5	10	15	30	60	90	5	8	10	20
	min	*min*	*min*	*min*	*min*	*min*	*hr*	*hr*	*hr*	*hr*
Watts	*105.3*	*69.0*	*48.0*	*28.6*	*14.9*	*9.8*	*3.1*	*2.0*	*1.6*	*0.9*
Watt-Hrs	*8.8*	*11.5*	*12.0*	*14.3*	*14.9*	*14.7*	*15.5*	*16.0*	*16.0*	*18.0*

Table 3. Prototype cell – Constant Power Testing Short Circuit Current 900-1,000 amps

Conclusions and Future Work

Though results to date are very preliminary we do conclude that the low aspect ratio cell design does show promise in its ability to deliver high power. The basic concept has been put into prototype form and will soon be taken to the next level.

Future work will begin by focusing on the optimization of the low aspect ratio cell design. Optimal grid, separator and paste thickness, paste formulations and tab designs will be the keys to further improving cell performance. Thinner separators and negative plates will lead to improved high-rate performance. Table 4 below is our estimate at the anticipated effect of these improvements.

The next phase of the project will involve optimization of the thermal management system and will involve thermal testing of cell stacks. Testing will be conducted to quantitatively evaluate the ability of the open core design to reduce the operating battery temperature. The ratio of the OD: ID of the cell will be further evaluated and its ability to control thermally manage the cells. All end cells will be thermally insulated so all cells experience similar thermal conditions and the distribution of cell temperatures within the battery pack will be quantified.

Run Time	5	10	15	30	60	90	5	8	10	20
	min	min	min	min	min	min	hr	hr	hr	hr
Watts	128.7	84.4	58.7	34.9	14.9	9.8	3.1	2.0	1.6	0.9
Watt-Hrs	10.7	14.1	14.7	17.5	14.9	14.7	15.5	16.0	16.0	18.0

Table 4. Optimized Cell – Constant Power Estimates