INVITED PAPER

Advanced Lead–Acid Batteries and the Development of Grid-Scale Energy Storage Systems

This paper presents a summary of advances in lead–acid batteries and the deployment of energy storage systems utilizing advanced lead–acid batteries for renewable-energy and grid applications.

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ABSTRACT | This paper discusses new developments in lead-acid battery chemistry and the importance of the system approach for implementation of battery energy storage for renewable energy and grid applications. The described solution includes thermal management of an UltraBattery bank, an inverter/charger, and smart grid management, which can monitor the state of charge (SoC) and the state of health (SoH) of the battery during system operation. With such features, it can allow the battery to operate within an optimum SoC window and thus can further maximize the longevity of the UltraBattery. Importantly, the smart battery management can trend the SoH of the battery and allow cell replacement at a convenient time without affecting the system operation. Furthermore, the advanced system package allows remote monitoring and control of operation, thus reducing the running cost of the system. It is clear that the widespread use of renewable-energy systems, in turn, would lead to a reduction in global consumption of the limited supplies of the fossil fuels and in the associated production of greenhouse-gas emissions.

KEYWORDS | Batteries; battery management systems; energy storage; power grids; smart grid

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I. INTRODUCTION

Energy storage has been recognized as an essential component of significantly increasing the penetration of renewable energy generation and is now the focus of significant government and private efforts [1].

Energy storage approaches include: potential energy such as pumped hydro, thermal energy in storage such as molten salt, kinetic energy in flywheels, compressed air energy storage (CAES), electrical energy in capacitors, and electrochemical energy in batteries. While pumped hydro is low cost, there are geographical limitations with this technology and, of the other technologies, the trend is toward batteries.

The battery space is currently dominated by lead–acid and lithium technologies. This paper describes 1) the development of lead–acid battery technology; 2) how the latest generation of carbon-enhanced designs is able to satisfy modern utility-scale applications; and 3) how system design is leading to a further evolution of valve-regulated lead–acid (VRLA) cells at a system level.

II. ADVANCED LEAD–ACID BATTERIES

Gaston Plante assembled the first known lead–acid cells over 150 years ago and lead–acid battery technology saw significant refinement over the subsequent 100 years, although these designs would probably have still been familiar to Plante. Breakthroughs came in the 1960s [4] and 1970s [5] when it was recognized that a lead–acid battery could be constructed to support significant oxygen recombination in a similar manner to recombination in sealed nickel–cadmium cells of the period. This allowed the development of the sealed, low-maintenance, lead–acid battery: the VRLA cell. The first designs in the 1960s were based on immobilized, gelled, electrolyte and the designs of the 1970s led to the electrolyte being held in an absorbent glass mat separator between the electrodes. These designs are commonly referred to as GEL VRLA and AGM VRLA, respectively.

Although VRLA technology did not directly improve the longevity or power handling performance of lead–acid cells, it solved a major problem with lead–acid: the need for frequent maintenance or, conversely, the unreliability of poorly maintained cells. VRLA cells required minimal maintenance and their much lower electrolyte content meant that shipping and airfreight regulations and the design of battery rooms could be dramatically simplified, leading to lower life cycle costs of systems. The lower electrolyte content of VRLA cells did have a drawback in that VRLA cells were more prone to dryout failures than the previous generation of flooded cells. This is a problem that is minimized by temperature-controlled voltage management in modern battery management systems.

The Advanced Lead Acid Battery Consortium (ALABC) was formed in 1992 and has been a major sponsor of the advancement of a new generation of lead–acid battery design over the past 20 years. This research has included the investigation of performance limitations of lead–acid batteries. After high carbon content was found to provide benefits [2], the focus moved onto carbon-enhanced designs. Integrating carbon into the negative electrode of the cell has allowed VRLA cells to enter a new application space, cycling for extended periods at a partial state of charge (pSoC). This ability is essential for an energy storage system that is ready to either accept or release energy. A conventional lead–acid cell is typically held at full charge between discharge events and cannot accept any significant energy in this state.

As VRLA cells enter new application areas such as partial-charge operation, different failure mechanisms can dominate. The longevity of VRLA cells is determined by a number of failure mechanisms, typically positive grid corrosion, positive plate material breakdown/shedding, water loss (dryout), sulfation of the negative electrode, and electrolyte stratification [6]. Water loss and stratification tend to be general failure modes while positive grid corrosion is more associated with standby or float charge applications. On the other hand, cycling tends to be associated with positive material breakdown and sulfation of the negative electrode [7]. The failure of the positive active material (PAM) is related to the mechanical expansion and contraction that occurs as the material transforms during charge and discharge. The PAM material occupies a different volume when discharged compared with when it is charged. With cycling, the PAM gradually expands and conductive pathways within the PAM deteriorate. Most cycling experience with VRLA failure modes has concerned lower power, multihour charge and discharge rates; however, many utility energy storage applications require higher rate cycling. Results from Ecoult (Sydney, N.S.W., Australia) and East Penn Manufacturing Co., Inc. (Lyon Station, PA, USA) life testing indicate that grid corrosion and dryout are not significant, even after extended periods of rapid cycling at higher power levels.

Fortunately, failure mechanisms of VRLA cells tend to be associated with a gradual degradation of cell performance rather than catastrophic failure. The failure mechanisms of the previous paragraph result in a gradual increase in cell impedance and accordingly, measurement of cell impedance is a widespread technique for the monitoring of cell state of health (SoH). Many sites implement this as a periodic manual check, although automated systems can perform SoH tests while a system is operational. This allows the trending of SoH and scheduling of cell replacement at a convenient maintenance period before a cell failure takes a system offline.

Fundamental research under the ALABC has included the investigation of material impurities to determine benefits of different impurities or additives and maximum tolerable levels of impurities. Knowledge of maximum impurity limits is a significant benefit in the reprocessing of lead–acid batteries.

ALABC has also sponsored research that has demonstrated that some conventional VRLA designs can achieve significant partial charge operation as required by photovoltaic (PV) plant operation. VRLA tubular GEL cells supported 2100 cycles between 10% and 40% SoC at 40 °C (BAE OPzV cells, BAE USA, Somerset, WI, USA). This result has been extrapolated to 4000 cycles at 20 °C operation [10]. The intent of this testing was to evaluate cells for PV support. Since a 4000-cycle life is equivalent to 11–12 years of operation, this research shows the potential for systems to experience only a single battery replacement over the 20 year life of a PV plant.

The use of carbon as an enhancement to the negative electrodes of VRLA batteries has allowed a significant improvement in the ability of a VRLA cell to operate in pSoC for extended periods [3], [12]–[15]. ALABC has sponsored research into the best use of carbon including: the different possible methods of incorporating carbon in the negative electrode; the desired composition of carbon types (high surface area/low conductivity, high conductivity/low surface area, etc.); the possible degradation mechanisms of carbon; the possible introduction of new failure modes or acceleration of existing failure modes (e.g., dryout, etc.); and packaging aspects such as compression to help control positive electrode shedding. The use of carbon has taken a number of paths, initially with carbon seen as a conductive component of electrodes and, more recently, as a capacitive component of the electrodes [11].

Axion has developed an alternative design, the lead–carbon, or "PbC" cell, which is often described as an

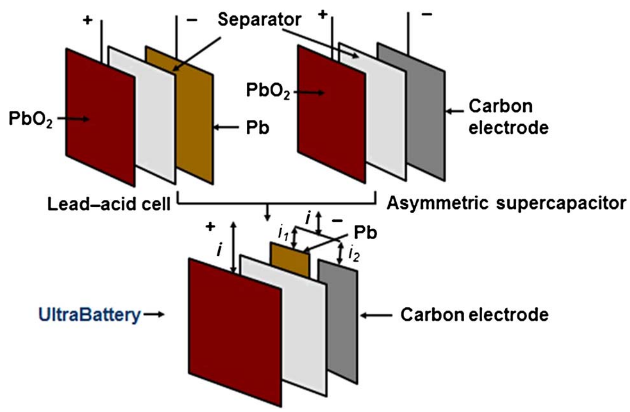

Fig. 1. *UltraBattery is a hybrid of a lead–acid cell and a supercapacitor.*

advanced carbon lead–acid battery. Nevertheless, it is different from a conventional VRLA cell in that the negative electrode is purely a carbon electrode, having more in common with design of an asymmetric supercapacitor [12]. Axion claims a high charge acceptance, a 4 times increase in cycle life (presumably over conventional VRLA), and improved ability of cells to balance their performance within a string of cells. Discharge of the PbC results in a wider voltage range than observed in VRLA cells. Unfortunately, a wide voltage range increases the cost of associated direct current/alternating current (dc/ac) conversion, or alternatively requires mitigation where some of the PbC cell capacity must be foregone.

Firefly International Energy Co. (Peoria, IL, USA) has a cell design that uses a carbon foam as a substrate for the active materials of the electrodes. Independent testing by the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) has demonstrated a 4 times cycle life improvement over conventional VRLA [13].

Work by Furukawa Battery Co., Ltd. (Yokohama City, Kanagawa Prefecture, Japan) [15] has provided some valuable insight into the contribution of construction of a carbon-enhanced VRLA battery toward cell longevity. In Furukawa's discussion of longevity, four of the seven factors investigated were related to control of PAM mechanical degradation. These were: compression of the cell, by far the most dramatic factor; additives to the PAM; separator elasticity; and PAM density. Control of electrolyte stratification and carbon in the negative active material (NAM) were lesser contributors, and the results from using various positive grid alloys were still under investigation.

Hitachi (Shin-Kobe Electric, Chuo-Ku, Tokyo, Japan) [14] has taken a very similar approach to Furukawa in its development of cells for utility-scale applications, with the aim of addressing durability of the PAM, charge acceptance of the negative plate, and stratification of the electrolyte. This result allowed Hitachi to claim a six to nine times improvement over its conventional AGM VRLA.

Furukawa did investigate the addition of carbon in the NAM; however, the contribution to longevity was much lower than from the control of PAM failure. At the time that Furukawa was designing these cells, carbon was seen as an enhancement of conductivity of the NAM. However, it was later shown that carbon can also provide a capacitive contribution.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO, Clayton South, Vic., Australia) and

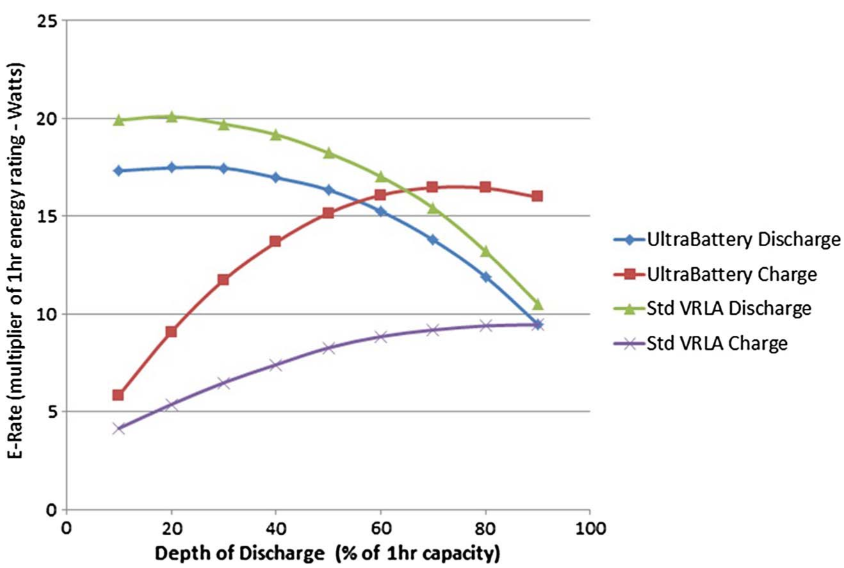

Fig. 2. *UltraBattery power handling capability.*

Table 1 Variance in cell voltage over time

Battery technology	Standard deviation 2011 (V)	Standard deviation 2012 (V)	Increase over 10 months
Furukawa	0.0168	0.0222	32%
Exide	0.0198	0.0694	251%
Yuasa	0.0186	0.0565	205%
Unigy II	0.0163	0.0391	140%

Furukawa [16]–[18] discovered that, rather than mixing carbon with the NAM, the carbon could be placed in a VRLA cell so that it was distinct from the NAM. This allowed asymmetric supercapacitor construction to be merged with VRLA cell construction producing the UltraBattery. The concept is illustrated in Fig. 1.

This is a different solution to Axion's PbC cell (described above) as the UltraBattery includes a conventional VRLA negative electrode design as well as a carbon electrode. The UltraBattery has a smaller dc voltage range than would be seen from a supercapacitor alone and, therefore, can use lower cost dc/ac conversion systems.

The integration of carbon and supercapacitor features allows UltraBattery to handle high power peaks and operate for extended periods in pSoC operation. It also results in long strings of cells being better balanced than seen in similarly sized strings of conventional VRLA cells. In a wind turbine power smoothing trial in Hampton, N.S.W., Australia, based on one string of 60 Furukawa UltraBattery cells and three strings of different conventional VRLA cells (each of 60 cells) the variance of UltraBattery cell voltages increased by only 32% over the ten month testing period compared to 140%–250% for the three control VRLA strings (Table 1).

The string capacities were slightly different due to different cell models and the four strings all had a 1-h discharge rate of 70–80 kW. Over the ten month period, each string saw a cumulative charge and discharge of 6.5 MWh. During power smoothing, the system controller maintained the SoC typically in a 45%–60% range.

UltraBattery has a slight decrease in power handling on discharge compared to conventional AGM VRLA; however, the charging power handling is significantly increased. Fig. 2 illustrates the pulse power handling of UltraBattery compared to conventional AGM VRLA.

Conventional VRLA and many competing battery technologies constrain operation in charge or discharge when SoC is in certain ranges. This significantly complicates or constrains system operation in grid roles. The much better balance between charge and discharge power handling means that UltraBattery can support symmetric charge and discharge and removes this system complication.

Fig. 3 shows two examples of UltraBattery cycling compared to a standard VRLA cell design. The data in this figure are a merge of the Sandia National Laboratories (SANDIA, Albuquerque, NM, USA) [3] and Ecoult test data normalized to the SANDIA test cycle. SANDIA testing was based on conventional VRLA cells compared to an UltraBattery design intended for hybrid electric vehicle (HEV) use. The Ecoult testing is based on cells that included UltraBattery carbon enhancements of East Penn VRLA AGM cell designs that are more robust than the HEV design used in the SANDIA testing.

The SANDIA testing was based on a small HEV battery that was exercised over a 10% range of charge, based on the 1-h rate. This was intended to emulate power smoothing as seen when cells perform grid regulation services (utility frequency regulation, etc.) The Ecoult

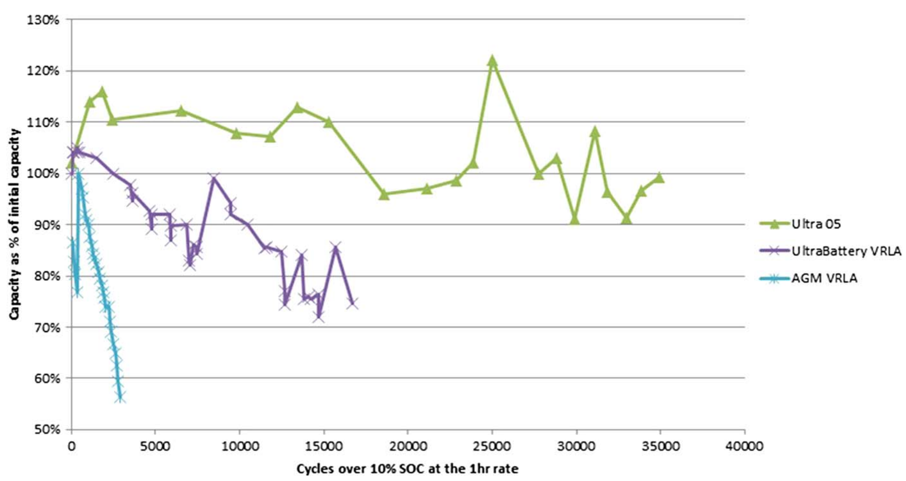

Fig. 3. ***Longevity of UltraBattery compared to conventional AGM VRLA.***

Fig. 4. *Public Service New Mexico PV and energy storage site, Albuquerque, NM, USA.*

testing was based on a string of 12 UltraBattery versions of East Penn Manufacturing's Unigy II AVR95-7 2 V cells. The Ecoult test profile presented the cells with a sinusoid of amplitude 1.3 times the 1-h discharge rate and a 200-s cycle period, superimposed on a slow baseline sinusoid of amplitude 0.15 times the 1-h rate with a 4-h period. The faster component is intended to provide throughput and the slower component results in a working SoC range similar to power smoothing duty. The Ecoult cells were operating in a 25 °C controlled ambient temperature.

The SANDIA cycle test was based on a charge and discharge cycle with throughput that was 10% of the 1-h rate. The Ecoult data were normalized to the SANDIA cycle data based on cumulative watt-hour (Wh) throughput and the 1-h rate.

The SANDIA testing demonstrated an order of magnitude improvement over conventional VRLA and subsequent, ongoing Ecoult testing on more robust cell designs is indicating an even more dramatic increase. This comparison is against conventional VRLA AGM technology. Higher cost, longer lived VRLA GEL technology would be expected to have a three to four times better cycling life than AGM. However, GEL batteries do not have the power capability of AGM, and the above data show that UltraBattery would still have advantage over VRLA GEL and at a cost more comparable to the lower cost AGM designs.

These improvements in cycling life mean that energy storage business cases that previously were not viable due to the need for a number of battery replacements can now be revisited.

The testing of longevity is a core activity of many advanced VRLA cell developments. In the past, cell longevity has typically been expressed as a number of cycles to a certain depth of discharge. This mapped to customer requirements of daily PV energy storage, daily motive battery discharge, uninterruptible power supply (UPS) backup, or Telecom backup. However, the utility storage world is characterized by pSoC operation and a variable pattern of charge/discharge and test methods are not so clear.

Grid operators have started to talk in terms of mileage over a working period which is the sum of absolute values of charge and discharge (watt-hour) over that period. Therefore, it makes sense to talk about system or battery longevity in terms of watt-hour over life. Some battery manufacturers talk about throughput which is the sum of all discharge watt-hours. Neglecting the effect of losses, a throughput figure could be doubled to give an equivalent mileage figure.

The Nippon Telegraph and Telephone Corporation (NTT, Tokyo, Japan) [7] showed that it is possible to accelerate testing of a cycling waveform by increasing amplitude and decreasing period. This meant that mileage

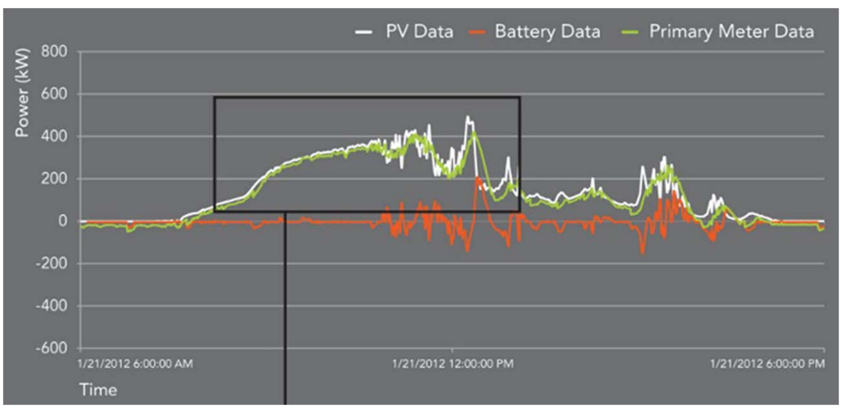

Fig. 5. *Smoothing of PV output with battery energy storage.*

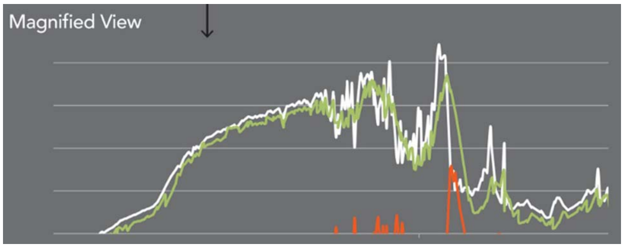

Fig. 6. ***Expanded detail from Fig 5.***

could be accelerated in testing. It also meant that use of a higher power, shorter period, activity was equivalent to a lower power, longer cycle activity, a justification that mileage could be applied to a varying power signal. Increasing cycling power by a factor and compressing time by the same factor preserves the depth of discharge in watt-hours. So the NTT data demonstrated that a cycling result could be scaled from one power level to another if both were over the same range of SoC. It does not support the use of accelerated test data obtained at one range of SoC to be applied to a different range of SoC.

Furukawa [15] showed the significance of PAM ageing on cycling longevity. As with accelerated testing, it was not clear that a mileage figure obtained from one SoC operating range could be applied to a different operating SoC range. The PAM of a cell is not a homogeneous material and degradation with expansion, and contraction accompanying charge and discharge obtained from testing over one range of SoC cannot be obviously applied to operation over a different range of SoC. Until the mechanism of PAM degradation for different SoC ranges is better understood, accelerated cycling testing should span the intended SoC range.

III. RENEWABLE ENERGY FIRMING

The intermittent nature of renewable energy generation adds additional variability to grid systems. As well as load variability, renewables create variability on the generation side. Utilities have implemented strategies for managing customer loads typically with incentives to maintain a steady load, payments to allow certain loads to be curtailed, or penalties for load peaks, etc. Similarly, as the amount of renewable penetration is increasing, utilities are placing constraints on the output of renewable generation plant. The most common form of constraint is ramp-rate limiting where a utility would typically specify that a generation facility should not ramp at more than 10% of the maximum output per minute. This tends to exclude residential plant and is more commonly a requirement when plants are of a commercial size.

An example of such a site is the 500-kW PV plant operated by the Public Service New Mexico (PNM, Albuquerque, NM, USA) (see Fig. 4). PNM has used this site to trial both power smoothing, or ramp limiting, and energy shifting [8].

Fig. 5 shows a 6 A.M. to 6 P.M. period on January 21, 2012, starting with a cloud-free region followed by a cloudy afternoon requiring power smoothing. The white trace is the PV output, the tan trace is the battery power, and the green trace is the smoothed connection power. Details of the algorithms can be found in [8].

Fig. 6 shows more detail of the boxed portion of the day's data from Fig. 5 (approximately from 8 A.M. to 1 P.M.).

As well as an UltraBattery power smoothing store, the PNM site includes a further battery store based on carbon-enhanced VRLA cells, intended not for power smoothing but for energy shifting. Fig. 7 shows an example of a PNM shifting algorithm where the battery was charged from a portion of the PV power during the morning, and then this charge was used to firm up the PV later in the day, creating

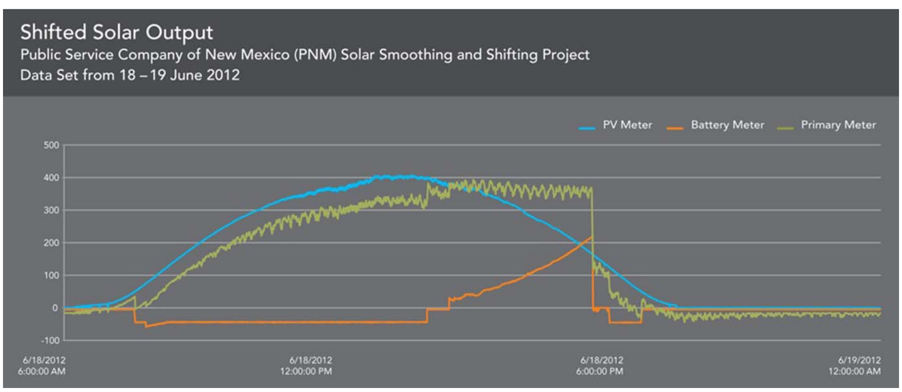

Fig. 7. ***Bulk shifting of PV output with battery energy storage.***

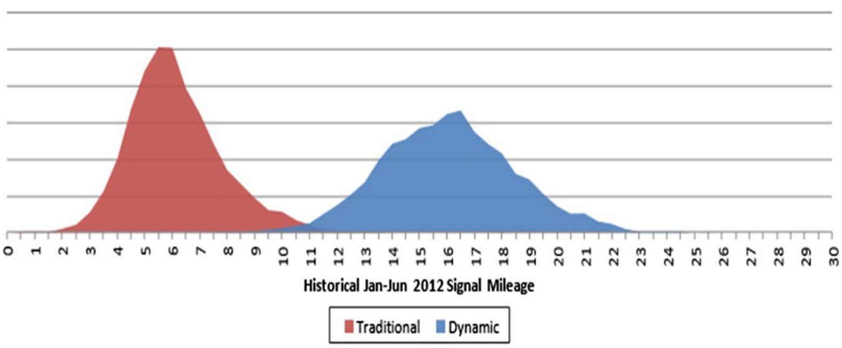

Fig. 8. *Higher throughput required from faster responding regulation resources, from [21].*

a rectangular power output profile that was easier to integrate into the PNM generator scheduling.

From the utility's perspective, wind farm generation firming is very similar to PV firming (i.e., ramp limit constraints) and, in some cases, energy shifting. There are many wind farm sites that have included significant advanced VRLA energy storage (e.g., the 15-MW wind farm operated by Kuroshio Wind Power Plant Inc. (Goshogawara City, Aomori Prefecture, Japan) with 10.4 MWh of battery storage).

Although many utilities are promoting the provision of energy storage at the points of generation, this is probably not the most efficient allocation of resources. For example, a PV plant of 20-MW capacity would require an energy store of approximately 15-MW peak power to manage ramp rate. With this ratio, the total energy storage on the grid would then be around 75% of the total PV capacity. Alternatively, if energy storage was managed by the utility, then the geographic dispersion of renewable generation provides some self-smoothing [9]. The total required energy storage capacity would be in the range of 5%–30% of the renewable generation capacity,[1] a fraction of the simpler fully distributed ramp-limiting model which requires storage capacity of 75%–100% of the renewable plant capacity. Grid constraints are a factor in optimizing the location of energy storage plant, and a mix of the two approaches, fully distributed and centralized, will be a likely outcome.

IV. UTILITY ENERGY STORAGE

As discussed in Section III, centralized management of energy storage allows a more efficient allocation of energy storage. The fast response time of battery energy storage compared to gas turbine generators has found promising use in grid frequency regulation (often abbreviated to "regulation"). Grid operators need to balance generation and load and tend to split this balancing into a number of components. On the generation side, the slower generators typically change hourly while generation associated with frequency regulation requires much faster response times. For a description, see [21]. Large grids such as the grid managed by the PJM regional transmission organization (RTO) in the northeastern United States are required to provide 0.7% of their demand in regulation services [22]. For example, at a peak load of 140 GW, PJM would need to allocate 1 GW of regulation.

Utilities are recognizing that frequency regulation can be further split into faster and slower responding components with the faster component being more compatible with the various forms of energy storage such as batteries. Analysis showed that a faster responding resource provides more benefit for system control than an equivalent-sized slower resource [26] and the U.S. regulator, the Federal Energy Regulatory Commission (FERC, Washington, DC, USA), encouraged utilities to take up such resources and implement a mechanism that rewards this improved performance benefit [27].

Fig. 8 shows that grid operators such as PJM are expecting that the faster responding resource will work harder than slower resources, typically having two and a half to three times the charge/discharge activity ("mileage") of traditional resources for the same nominal peak power capability. PJM calculates that faster regulation resources could address 40%–50% of its existing regulation requirements [22]. This indicates an existing U.S. market size of around 2 GW for fast-responding regulation. With renewable generation increasing, the demand for frequency regulation is expected to rise from around 1% of capacity to around 2%–7% of capacity, depending on network constraints, as wind penetration reaches 20% of capacity [23].

As an example of such a system, Ecoult and East Penn Manufacturing Co., Inc. have implemented a 3-MW UltraBattery plant in Pennsylvania, which has been

[1]Milborrow [23] estimated that an energy storage capacity of 2%–7% of system capacity was required when renewable penetration was 20% of system capacity. Hence, the incremental storage capacity from a 1% base is 5%–30% of the wind generation capacity.

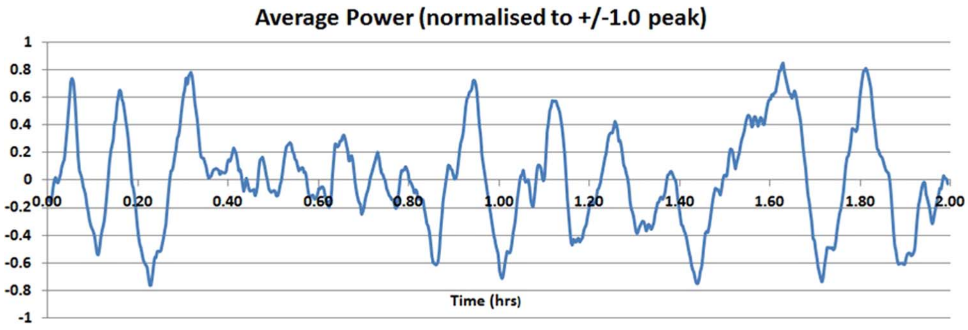

Fig. 9. *Example 2-h period of PJM dynamic regulation signal.*

operating since July 2012. This is based on four strings, each of 480 cells, with 750-kW dc/ac inverters.

Fig. 9 is an example trace showing a PJM frequency regulation signal for a 1-MW plant over 2 h [24]. The East Penn 3-MW system routinely achieves a PJM signal tracking accuracy better than 97%. The residual error primarily arises due to the system controller offsetting the power signal to draw SoC back to a target SoC operating point. Depending on system sizing, typical power regulation results in 10%–30% SoC range.

The above 3-MW example could be easily expanded to a more commercially scaled 20-MW system based on 28 battery strings, each of 480 cells and with individual 750-kW dc/ac inverter sections so that the power to each string could be controlled individually. This is one string more than required for a 20-MW rating and provides redundancy to allow string maintenance with no reduction of capacity, allowing higher reliability/availability.

With more centralized regulation as in the PJM model, an energy store operates continually, 24 hours a day, seven days a week. This has impact on both longevity and thermal management, and these are discussed under Section VI.

V. DUAL PURPOSING

Dual purposing of energy storage is seen as a way of improving the business case of a system so that overheads of an energy store can be distributed over multiple revenue sources. To date, optimizing different applications typically produces marginal results [25].

There is one case investigated by Ecoult that has significant benefits. That is the combination of a UPS together with the provision of a grid energy function, specifically regulation services. The two roles are very synergistic: when the grid connection is present, the system supports frequency regulation; and, when the grid is absent, UPS support is supplied.

Normally, a UPS battery is charged to 100% capacity and is discharged in a UPS event to a low cell voltage. UltraBattery is capable of working for extended periods at a partial charge. Therefore, we can install a slightly larger

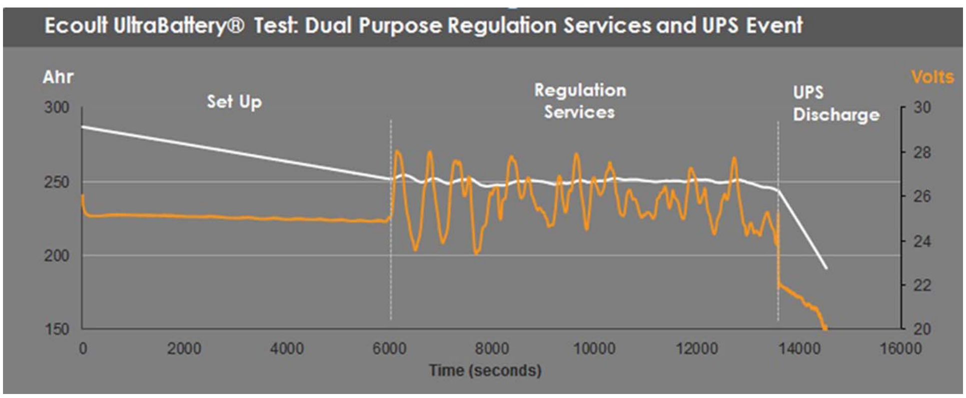

Fig. 10. *Test sequence illustrating period of power regulation followed by UPS discharge.*

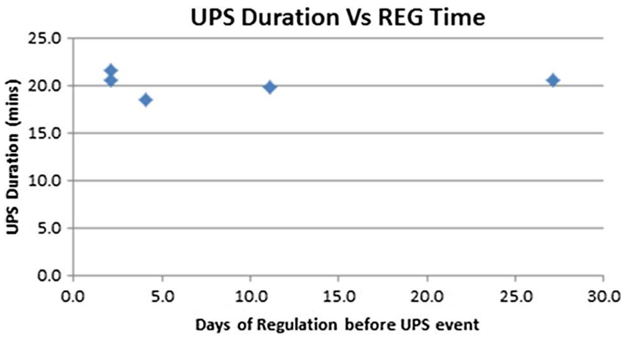

Fig. 11. *Negligible effect of duration of regulation on UPS discharge duration.*

battery store and operate at 75% SoC so that the battery can still supply the required UPS energy. As the battery is at 75% capacity, the battery can then absorb and supply power, allowing support of grid functions such as frequency regulation services.

Fig. 10 illustrates a test with an UltraBattery being initially taken to a pSoC, followed by a period of typical frequency regulation service and then a UPS discharge from a low state of charge point.

This example trace is based on a very short period of pSoC activity; however, these systems must be able to provide extended periods of regulation activity. Fig. 11 shows that UltraBattery can operate for at least around a month providing regulation service with no degradation in UPS discharge capacity.

With this dual-purpose UPS and regulation role, the infrastructure of a typical $2N+1$ redundant UPS, including switchgear, transformers, wiring etc., aside from the battery, does not require any increase in capacity. The additional cost of this dual purposing is, therefore, only the increase in battery size, a small portion of the total UPS cost. This is offset against a revenue stream from the provision of regulation services.

With conventional UPS systems, batteries are on standby most of the time with only a low charging current applied. The ability of the battery to support a high load UPS event is not obvious with only low power applied. With dual purposing, the battery is supporting high load regulation services on an ongoing basis, and the ability to manage a UPS event is much clearer.

VI. SYSTEM DESIGN

Large VRLA cell systems have historically been used for standby power applications. System management of these systems involves: float charge, cell voltage monitoring, cell impedance monitoring (SoH), and data logging. The system controller must also manage discharge and charge to support UPS events and cell replacements.

With grid-scale energy storage, power smoothing is common and cells are now working at much higher average power levels than in previous applications. This introduces new thermal management issues, changes cell behavior, and risks introducing the potential failure modes discussed earlier. Cell racking and cell designs, which were appropriate for standby power, require adaptations for these new applications, most commonly involving changes in ventilation techniques [19]. It is not unusual for cells performing high power smoothing to see temperature rises of 10 °C–15 °C above ambient. This sort of thermal problem is well known in the HEV space [29], and these design techniques and solutions are now being applied to grid battery systems. Fig. 12 shows an example computed fluid dynamics (CFD) model of temperature and airflow over a stack of ten East Penn cell modules to evaluate temperature rise with a rear ventilation mechanism. This analysis was based on cell models with uniform heating throughout the cell body. Fig. 13 shows an alternative technique based on a thermal finite element analysis (FEA) mesh model of East Penn cell internal space and cell module housings. In lead–acid cells, Fig. 13 illustrates calculated temperature rise from lower most cells to higher cells in a stack. Fig. 14 shows a thermal image used to calibrate the CFD and FEA models. Cell temperatures of up to 36 °C–40 °C highlight the importance of system cooling design when cells are required to operate in power smoothing roles.

In lead–acid cells, higher cell temperatures do not lead to the fire risks that are associated with some other battery

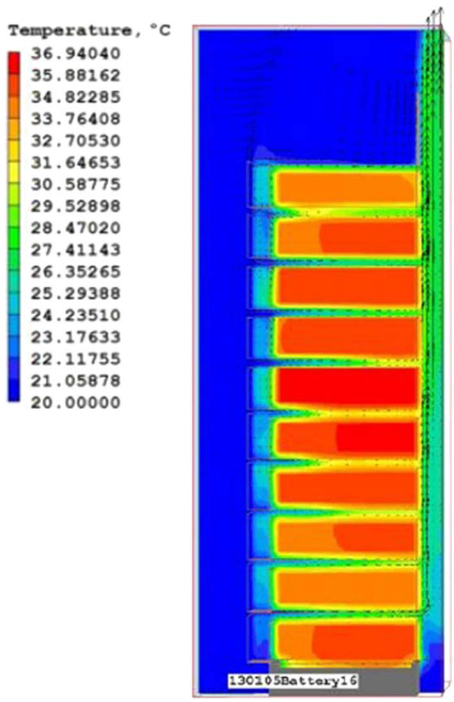

Fig. 12. *CFD model of cell stack.*

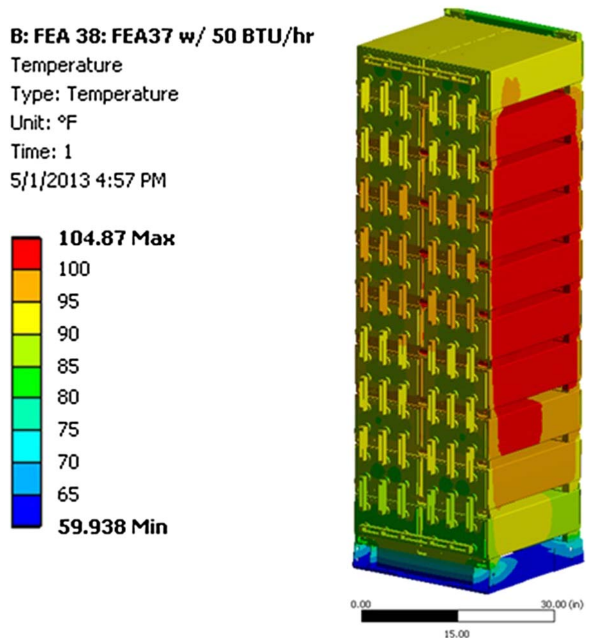

Fig. 13. ***Thermal FEA mesh model of East Penn cell internal space and cell module housings.***

chemistries, but higher temperature does increase conductor resistances, and accelerate electrochemical and diffusion processes. There are many such pathways involved in VRLA operation with some pathways synergistic to cell performance and some competing. The net effect of temperature on different failure mechanisms with cycling duty and resultant longevity is, therefore, not obvious. The industry expects that increased temperature will result in a shorter cycling life [10], [20].

The improvement of power handling is reasonably clear with increased temperature. Ecoult testing based on the sinewave power smoothing profile described in Section II, advanced lead–acid batteries, on a 12 cell UltraBattery in UB95-7 format resulted in cells at the top of a stack being hotter than the bottom most cells. This arrangement confirmed that power handling was improved for warmer cells with peak–peak voltage 2.5% lower for cells at 40 °C than for cells at 34 °C. The ambient temperature was 25 °C.

During continued pSoC operation, the impedance of cells rises due to short-term effects such as sulfation and longer term cumulative ageing effects. The short-term effects are managed via periodic refresh charges.

Fig. 15 shows increasing maximum and minimum string impedance for a 24-V UltraBattery string of cells with an Ecoult sinusoidal test waveform described in Section II. The plot is from a 12 cell string of UltraBatteries in the Unigy II AVR95-7 format. The impedance is calculated as the peak–peak sinusoid voltage divided by the peak–peak current. The plot shows how impedance increases over time, and the fall occurred when a refresh full charge cycle was performed. The throughput between refresh charges is equivalent to 60 days of 24-h real-time power smoothing duty. Work on enhancement of UltraBattery continues to even further extend the duration between refresh and lifetime throughput.

Ecoult testing showed that temperature accelerates this increase such that warmer cells lose the initial performance advantage and, after a couple of months of full-time pSoC regulation duty, can have lower performance than cooler cells (based on test cells at 40 °C versus 34 °C). The performance was restored by taking the cells to a full charge. Production systems require periodic downtime for such charge cycles. Larger MW scale systems are designed with one or two redundant battery strings to meet customer reliability requirements, and these strings mean that a full charge can be performed on one string without loss of system capacity.

The range of cell temperatures over a battery string should be controlled for uniform cell performance so that individual cells are not exposed to conditions that would result in premature failure of such cells due to imbalance resulting in overvoltage stresses, etc. Industry standards have been developed that recommend a maximum 3 °C cell temperature variation [28]. However, these standards have been developed for VRLA float conditions, and it is not obvious that this range is appropriate for power smoothing duty. Until further data are available, system design will be based on this range.

In the past, the longevity of battery systems has been expressed as a cycle life typically at a specified depth of discharge as this mapped directly to customer requirements such as daily PV storage, Telecom backup, UPS discharges, etc. This simple cycle model does not fit with emerging grid storage applications. The longevity of grid storage systems when processing arbitrary power regulation signals is typically expressed as a total mileage, commonly watt-hour per watt of peak rated output.

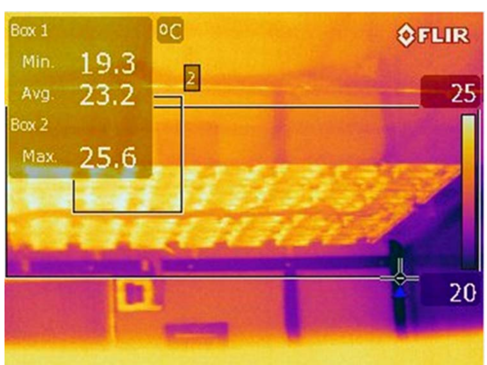

Fig. 14. ***Thermal imaging of operating East Penn cell stacks. The camera is rotated 90° such that the top of the stack is on the left.***

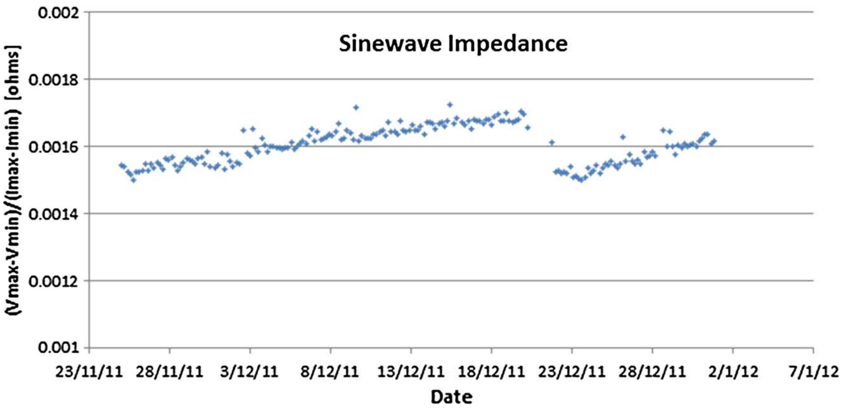

Fig. 15. *Cell impedance increases with power smoothing activity and is refreshed to a lower value with a full charge cycle.*

The voltages of all cells are monitored so that individual cell SoC and SoH can be determined. SoC of a cell cannot be directly measured and is commonly synthesized from history of voltage and current of a cell. Such algorithms attempt to model the consumption or regeneration of cell active materials during use and must recognize that the capacity of VRLA cells varies with the level of discharge or charge rate.

Sample cell temperatures are measured throughout the strings to monitor temperature distribution patterns within the strings to support thermal management within a string. The battery room or battery enclosure requires ventilation and temperature control. The system controller determines a system SoC for multiple strings and reports this to the customer interface. The system controller then apportions requested power flow across the different strings to align SoC between strings. Battery monitoring systems commonly support trimming of the SoC of individual cells to bring them into alignment.

Fig. 16. *Pallet-sized outdoor battery packaging.*

System activity, summary cell data, and cell SoH trending are logged by the system to a database remote to the plant, and monthly reports on system operation allow the scheduling of any required maintenance.

Mechanical packaging for thermal reasons is one aspect of packaging but another concerns site assembly. Many customers are interested in containerized solutions and SANDIA was promoting such systems as early as 1994 with its PQ2000 design [30].

The intent of system design is to develop solutions that allow most assembly to occur in a production environment and result in a minimum of assembly at customer sites. Factory-assembled modules, as illustrated in Fig. 16, should be able to be transported by a majority of standard freight techniques. Modules should be flexible so that they can be installed with or without weatherproofing and heating, ventilation, and air conditioning (HVAC), so that they would be compatible with either building installations or outdoor installations, as building installations can achieve lower costs if construction resources are near a project site.

VII. CONCLUSION

The significant advances in VRLA technology over the past decades have allowed lead–acid batteries to provide power handling performance and longevity competitive with other battery chemistries while being based on a technology that is well known in the industry, supported by proven transport, fire codes, building codes, and other safety standards as well as a mature, nearly 100%, recycling process.

The recent development is partly evolutionary, but a significant factor is the use of carbon as an enhancement of the negative electrode. This allows VRLA cells to operate for extended periods at a partial charge, facilitating operation in utility applications where the energy store can be called on to absorb or release energy.

New breakthrough technologies such as the CSIRO UltraBattery technology offer a combination of high rate charge acceptance and discharge capabilities with pSoC that allows lead–acid chemistry to match and exceed competing chemistries in endurance, efficiency, and power handling.

Multiple megawatt-scale VRLA battery sites are now operational, and the experience with these sites has led to further advances in cell design for increased peak power handling and the design of battery management methods and systems to minimize initial system costs and maximize the longevity of cells in these applications.

Based on the experience gained over the past decade with initial megawatt scale systems, a new generation of VRLA cell designs, system designs, and packaging are now emerging that are both lowering the cost of MW scale systems and improving performance. ■

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