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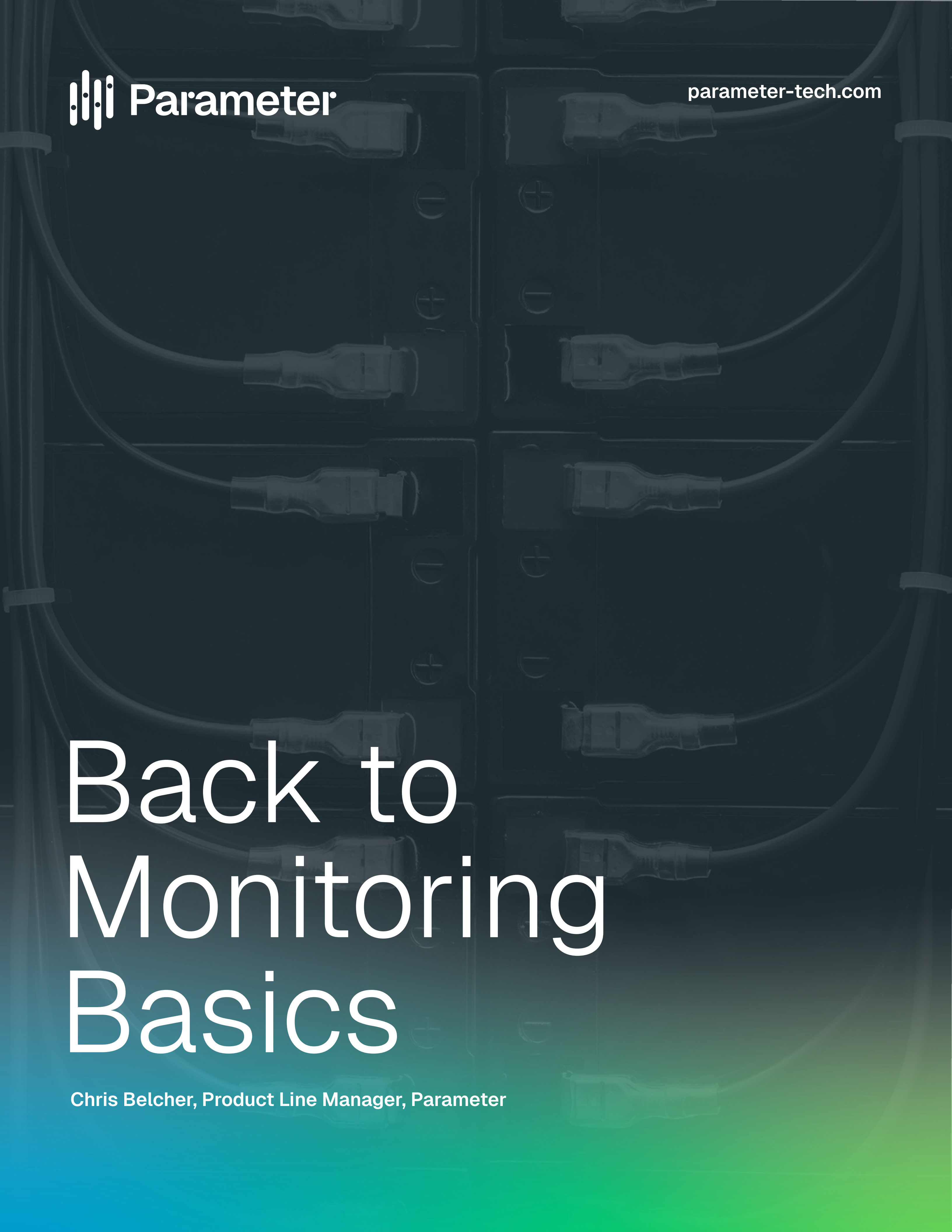

Back to Monitoring Basics

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Batteries continue to be a significant component in many applications in today's world. Battery technologies utilized for cycling and standby energy storage systems include lead-acid, nickel-based, lithium-ion, and sodium-ion chemistries, as well as other new and emerging technologies yet to become main-stream. Each chemistry has distinct advantages and disadvantages over other chemistries and all perform the same function, to store energy for use at a later period in time.

The importance of these battery systems varies by customer, application, and location. A cell phone battery often is not of the same importance as a UPS battery system supporting a hospital, 911 emergency call center, or data center. Regardless of the importance, we still expect that the battery will be ready and available whenever needed. Should the battery be unavailable when needed, customers may face financial losses, fines, or system down-time. For example, a cell-tower backup system may not cause significant financial impact but may face additional scrutiny and fines for not supplying 911 emergency services. An unavailable data center backup battery could cost the company millions in lost revenue after just a few minutes, reputation issues, and significant customer impacts to hosted services.

To help ensure these battery systems maintain a high level of system availability, users should maintain adequate maintenance practices, which may vary depending on the criticality of the application. To help facilitate collecting data for those maintenance practices, users can rely on automated monitoring to provide additional insights into the performance of the battery system.

All battery chemistries require some form of maintenance along with manual measurements or automated monitoring requirements to provide snapshots of the conditions and health of the battery system. Automated monitoring systems provide increased insight into these parameters and conditions and can provide users with information to manage the health of their battery system. These systems are often referred to as Battery Monitoring or Battery Management Systems.

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Both Battery Monitoring Systems and Battery Management Systems are often referred to as the BMS, though there are key differences between the systems. Battery Monitoring Systems are used to monitor the parameters and conditions of the battery. The most basic system is typically a system level measurement, such as string voltage and float current, that provides limited insight into the state of the system. More advanced systems can provide individual cell or unit-level measurements with trending analysis to provide insight into changes within the battery system. Figure 1 below shows the typical parameters and outputs a battery monitoring system. Battery Management Systems are often more complex, but will include some form of a Battery Monitoring System and add an element of control beyond the monitoring functions. The active function of control is the differentiator between a passive monitor and an active management of the battery. A Battery Monitoring System may be installed in each module individually and a System Controller or higher-level Battery Management System to make control level decisions.

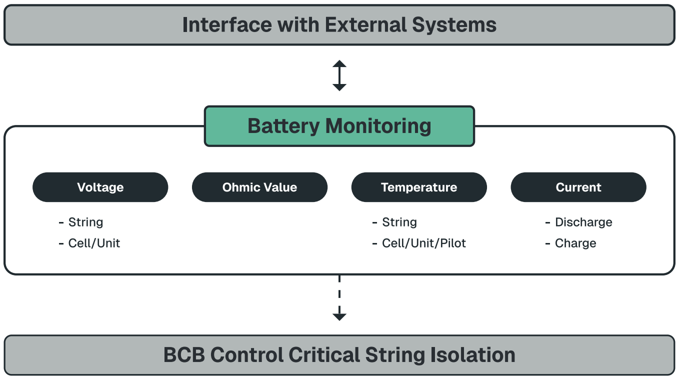

Figure 1 - Representation of Battery Monitoring System Parameters and Outputs

These systems take an active role in managing operational conditions, charge capabilities, and in some cases discharge capabilities for the battery system. These systems are utilized andnecessary in many of the newer advanced technologies such as lithium-ion and sodium-based chemistries. Figure 2 below shows the typical monitored parameters and controls a battery management system may utilize.

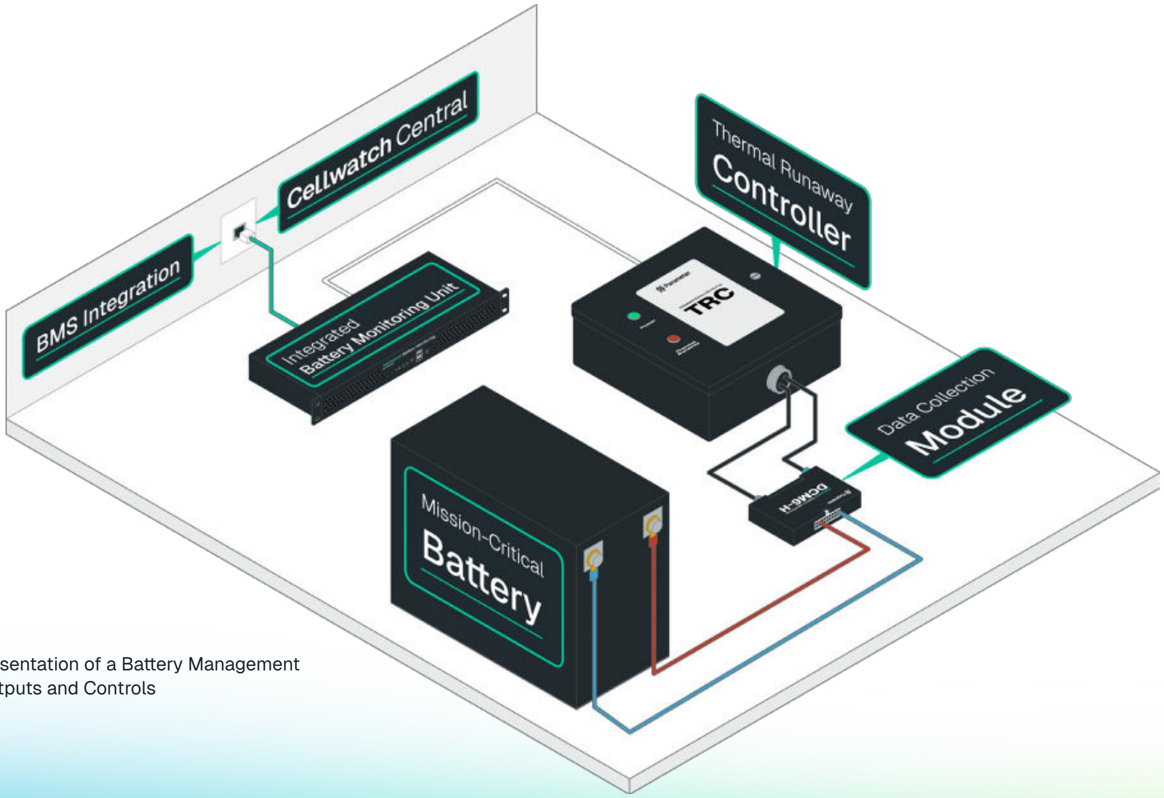

Figure 2 - Representation of a Battery Management System with Outputs and Controls

It is important to note that not all chemistries require battery monitoring or management, but many will often benefit from some form of continuous monitoring. In either system, real-time metrics are made available for external integration. Some systems may provide historical trends, real-time graphing, or active alarm conditions for users to monitor, detect, and take action to resolve the issues. This is more common in battery monitoring systems due to the lack of control of other operating parameters. Management systems will often attempt to control the parameter and may reach a point where the condition is no longer controllable.

This paper will focus on Battery Monitoring Systems and will be referred to as BMS. While the focus of this document will be on battery monitoring parameters, it is important to note the differences between monitoring and management systems and key resources for both.

Two key resources are: IEEE 1491 – Guide to the Selection of a Battery Monitoring System and IEEE 2686 – Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications, these documents serve as two guiding documents on parameters and functions of Battery Monitoring and Battery Management systems.

This paper will review many of the key monitoring parameters that are used in the decision-making process for these systems and highlight the importance of trending and proactive responses to alarmed conditions. This paper should not be viewed as the definitive list of measurements or methods for monitoring.

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Voltage Measurements

Voltage measurements are one of the most basic measurement functions within any battery monitoring and battery management system but also is one of the most troublesome measurements to use in a battery system. The most primitive form of voltage monitoring in a battery system is the string voltage. Additional monitoring equipment often allows monitoring voltage of segments within the battery string or individual units or cells within the string. Unit level monitoring is often necessary in determining which cells in the system are underperforming or at risk, this requires additional components and therefore results in an increased system cost. Figure 3 below illustrates the basic concept between string level vs unit level monitoring.

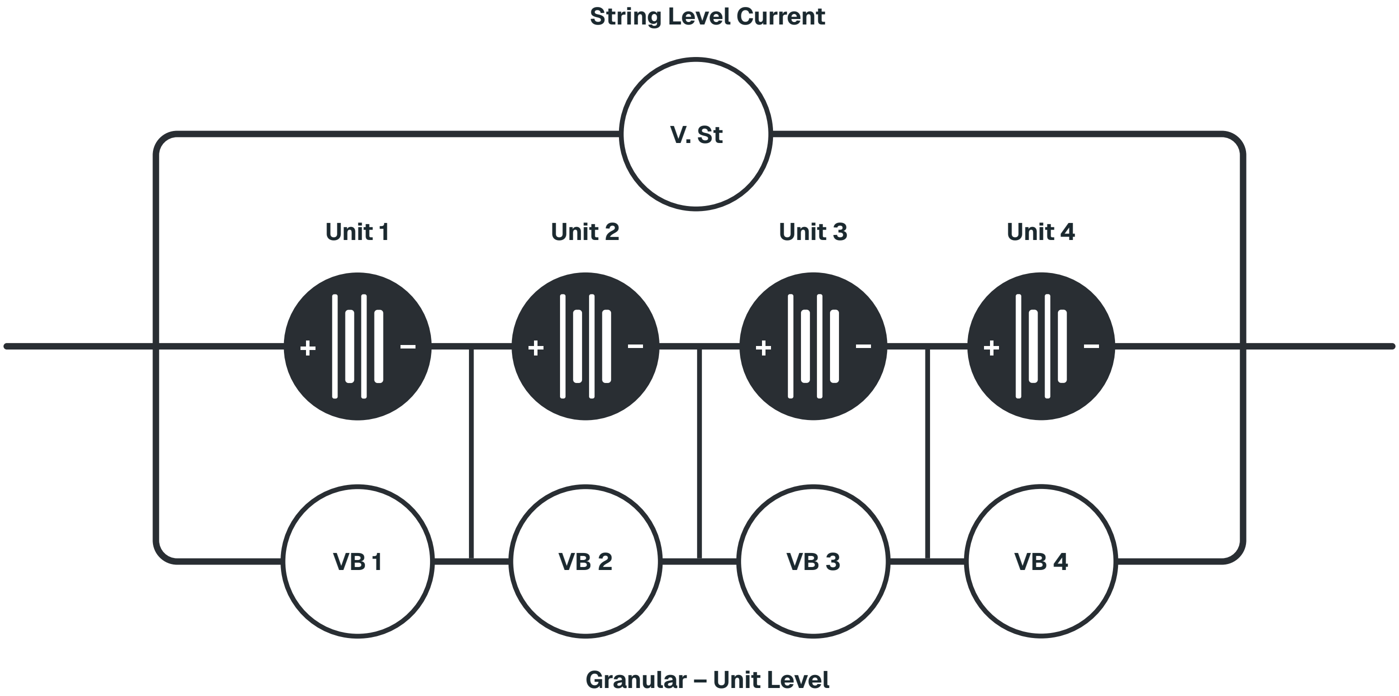

Figure 3 - Illustration of String Voltage vs Granular Voltage Measurements

The most meaningful voltage measurement that can be taken is the Open Circuit Voltage or offline voltage reading. This open circuit voltage reading can sometimes be correlated to capacity for some, but not all, lithium chemistries or the specific gravity of lead-acid chemistries. To get this open-circuit voltage reading, the battery often must be taken out of service for an extended period of time which may not be possible for many applications, particularly those in Standby UPS deployments.

If the battery must remain in-circuit and online during testing, then measurements may vary depending on the charger, parallel connections, state of charge, float state, or discharge state. Battery Specialist often refer to these measurements as real-time voltage measurements. If a battery is at 100% State-of-Charge (SOC), we often refer to the voltage measurement as the float voltage measurement. If the battery is in discharge we refer to the voltage as the discharge voltage measurement.

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Voltage in these states can change very rapidly and will vary depending on cell temperature, cell SOC, and float status.

Depending on the chemistry of the battery system, a battery management system may be added to control the voltage of the cell. For example, cell-balancing or cell-limiting functions may be used to

Trending Voltage

Trending of voltages can be done if assuming common state characteristics. Cell float voltages, for example, can be trended over time if the measurement has a similar state of charge for long periods of time.

In a standby battery, float voltage is typically a 100% state of charge maintained through the majority of the life of the battery. A full state of charge condition is common in standby UPS applications, but less common in cycling applications where the battery charges and discharges several times per day. With a common state of charge, cell deviations from the rest of the system become more apparent and can help identify underperforming or unusual string behaviors.

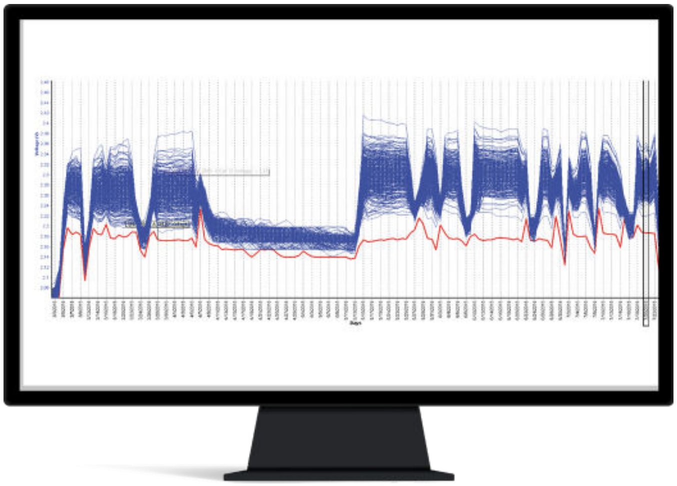

Figure 3 - Illustration of String Voltage vs Granular Voltage Measurements

Figure 4 left shows both online and offline impacts on a battery string. As noted, voltages can vary quite rapidly, and problematic cells can begin to show themselves as they differentiate from the rest of the string. These cells can cause change stresses in the battery string impacting other cells/units. During charge and float, the unit voltages above span a broad range, and the offline voltages show a much more condensed spread of voltages. Note the outlier colored in red that remains low consistently during charge, float, and offline conditions.

Equally, trending discharge voltage performance can become quite important, assuming other key characteristics such as the system load, remaining consistent. Discharge events can highlight underperforming or weak cells within a battery string.

When cell voltage is trended over time or compared with other cells in a string, it also serves as an indicator for the cell State-of-Health (SOH) relative to other cells within the battery string. Often cells that begin to fail over time will begin to deviate with float voltage or discharge performance.

Special consideration should be taken for varying ambient temperature and temperature compensated charging circuits.

Current Monitoring

Depending on the application, a BMS may monitor discharge current or charge currents, and in some cases both. At a minimum battery level, current should be monitored. Battery level monitoring does not provide any information on current flow within the individual strings. Additional probes may be used to monitor parallel string currents. Figure 5 below illustrates the battery level and string level current probe placements. Often parallel strings that are balanced will have similar discharge performance characteristics. String voltages often begin to vary significantly as individual cells deteriorate in performance within a string.

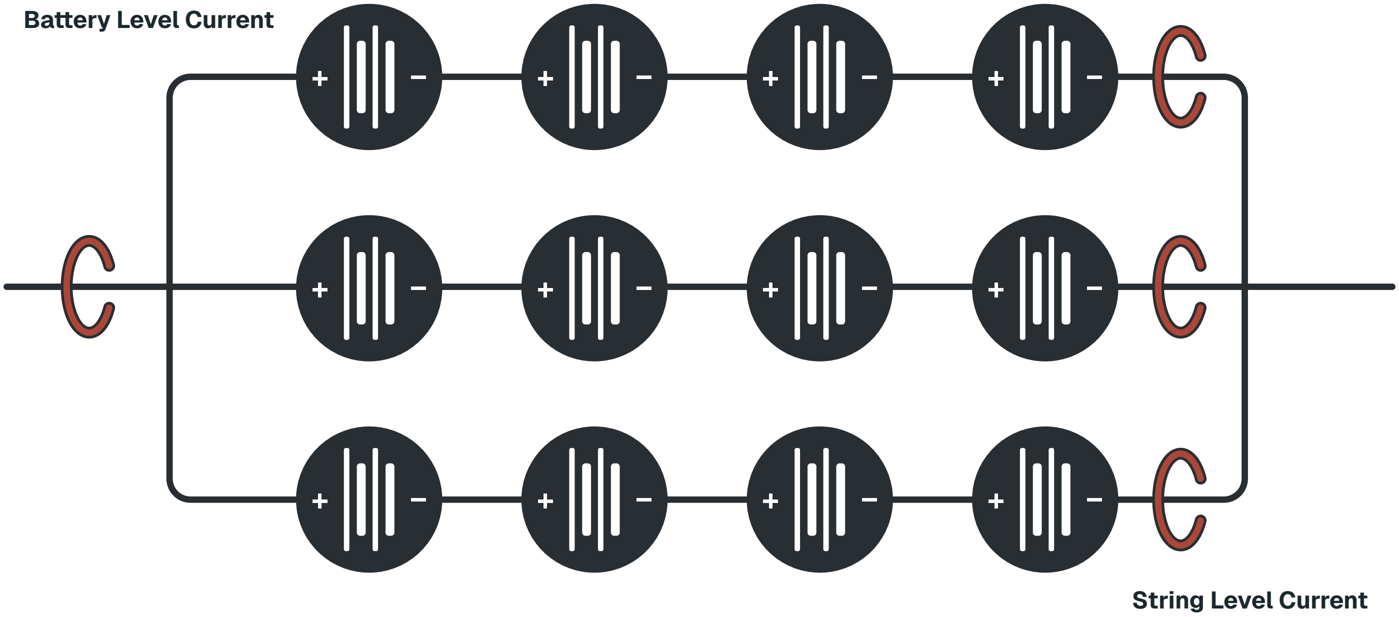

Figure 5 - Illustration representing Battery Level vs String Level current probe placement

Float current is often not required for continuous monitoring on large-scale battery deployments but may be a requirement for some applications. For example, float current is often utilized for regulatory compliance, such as NERC.

Chemistries that utilize battery management systems often require continuous current monitoring during charge and discharge functions, so the battery does not exceed safe operating limits potentially damaging the cells. However, string level measurements need to take into consideration any net cell-balancing currents and module BMS currents that may vary between string units or voltage tiers within a unit. These systems may use another form of current monitoring such as coulomb counting, a running summation of current flowing in and out of the battery every second.

Chemistries such as lithium iron-phosphate (LFP) or lithium titanate (LTO), may incorporate a battery management system that incorporates cell, tier, or module level coulomb counting to better understand the amount of stored or released energy from the battery. This is often because battery chemistries such as LFP have a very stable voltage between 20% and 97% State-of-Charge (SOC) and using voltage alone to determine the approximate capacity is not possible.

Battery management systems will often monitor and manage the current flow to manage the state of charge of the battery system. For example, current flow must be arrested to prevent overcharge or over discharge conditions for lithium-ion chemistries. A monitoring system will not utilize these functions to control/protect the battery and leave control of the current flow to the DC charger or the Uninterruptable Power Supply (UPS) system.

Current Trending

Figure 6 - Screenshot of Cell-Level Discharge Voltage Performance and String Current

Float current is typically trended over time for standby battery applications. This is often because a standby battery system remains at 100% SOC for much of the battery life. Increases in float current over time can sometimes indicate changes within the cell chemistry or potential issues such as thermal walkaway.

Discharge current performance may be compared over time assuming the load profile remains similar between discharge events. In these events, parallel strings can be compared to each other, and the strings prior discharge performance can be compared with the most recent discharge event. Changes in discharge performance, such as a rapid increase or decrease in string current, may indicate a failure present the battery system. Figure 6 above shows string level discharge currents (green) and unit voltages (blue) during a discharge event. In the example above, a cell failure resulted in a decrease in the string current and an increase in current flow in the parallel strings.

Ohmic Value Monitoring

Ohmic value is an internal impedance measurement of the cell or unit often reported in milli-Ohms (mΩ) or micro-Ohms (μΩ). This value is often used to help determine the SOH of the cell but has different meaning and applicability for different chemistries. For example, Lead-Acid can vary in ohmic value, however, Nickel-Cadmium batteries (Ni-Cd) often do not change in ohmic value. In lead-acid chemistries, Vented Lead Acid (VLA) is typically measured in micro-Ohms (μΩ) and Valve Regulated Lead Acid (VRLA) is measured in milli-Ohms (mΩ) due to the size and conductance of the cells. Often ohmic value is often impacted by a variety of elements such as sulphation of the plates, electrolyte conductivity, welded inter-cell connection integrity, impacts to grid-continuity, post torque, and SOC.

For relevant chemistries, an increase in ohmic value of 30 to 50%, typically for lead-acid chemistries, or 200 to 400%, for lithium-ion chemistries, is generally considered end-of-life. This varies depending on the battery chemistry selected. A change could also indicate a failed component within the battery system like changes torque on terminals.

It should be noted that some battery management and some battery monitoring systems do not collect ohmic value measurements.

Ohmic Value Trending

Ohmic value trending can be a valuable tool in assessing changes in the battery system over time. This measurement can indicate a variety of failures such as dryout, corrosion or sulphation of the plates, or defective conductive paths within the cell. It is important to note that ohmic value can change depending on the state of charge of the battery system, so it is often not used in cycling applications unless the measurement is taken under common battery conditions.

Figure 7 - Screenshot of Historical Ohmic Value and Historical Cell Voltage

Figure 7 left shows a battery string that is beginning to deteriorate. The issue was identified immediately when the units began to fail, however, in this case the unit wasn't replaced for months.

Ohmic readings are most effective when captured at a similar state of charge and temperature as changes in these parameters can impact the ohmic value. For example, the resistance of electrolyte and the metals within the cells will change as the natural temperature fluctuates, even with a full SOC. With consistent conditions the ohmic value reading will provide insight into the internal SOH of the battery cell. Trending can still occur without consistent variables, but interpretation of the data should be done more carefully.

Temperature Monitoring

Temperature measurements can vary depending upon the placement of the temperature probe locations. Users should consider the impacts of HVAC and airflow in and around the battery string and the impact on the temperature readings. At a minimum it is recommended to have ambient and a pilot cell within a battery string. However, depending on the application and the battery chemistry, it may be suitable to use a single pilot cell or for increased granularity of readings, temperature readings captured at every cell. Some chemistries and module designs require more than one temperature reading and measurements in close proximity to cells to properly characterize the temperatures within the module.

For example, a battery cabinet comprised of 40x 12V VRLA units might be suitable with a single temperature monitor at the top of the cabinet. An open stack of 240x 2V VRLA or an open rack of 60x 2V VLA units might be more suitable with temperature monitoring on the negative post of every cell or every couple of cells. A lithium-ion battery system may utilize multiple temperature probes throughout a battery pack to capture the temperature throughout the module.

Temperature Trending

Often temperature is trended over time to determine if the battery is regulated in suitable conditions to meet design life. Battery manufacturers specify an appropriate temperature range for the proper operation of the units. Battery temperatures that are too hot can accelerate grid corrosion, and when too cold could result in reduced performance. Temperature trending could also be used to help approximate the estimated expected life of the battery system. For example, for roughly every 10 degrees C above an optimal 25 degrees operating temperature, a lead acid battery's grid corrosion is doubled, thus reducing battery life by half if continuously operated at that temperature.

Temperature trending in certain chemistries, such as lead-acid, could also be indicative of potential thermal walkaway conditions. It should be noted that often when this condition arises, there are other parameters within the battery string that are indicative of an impending thermal event. Rising temperatures should be investigated to ensure safe reliable operation of the battery system.

Figure 8 - Screenshot of Historical String (Cabinet) Temperature with Cell Voltages in a System in Thermal Walkaway

Figure 8 above depicts a thermal walkaway event in a VRLA lead-acid battery with parallel strings. This battery system was floating at a normal, acceptable voltage, but was defective. In this situation, the battery string did not receive enough airflow which contributed to the thermal event. Note the continued increase in temperature (red) of the string and parallel cabinets impacted. Also note the voltage drop (blue) in a unit of the impacted string and the corresponding rate of temperature increase.
Battery management systems may monitor cell or tier temperature measurement to ensure cells do not enter an over or under-temperature condition and may isolate the battery string until temperatures return to normal operation. A battery monitoring system can provide early detection and warn an operator often weeks or months before any serious conditions arise.

Combined Alarms

When two or more alarms occur on the same cell/unit, then a potentially compromised cell/unit in the battery string is almost always confirmed. In Figure 9 below, we see a highlighted cell (red) voltage that is gradually failing and an ohmic value reading for the same cell slowly increasing in value. In the graph, voltages are depicted as blue and ohmic values are depicted as yellow. As shown in Figure 9 below, once replaced, the new cell ohmic value drops below the majority of the string and the voltage of the replaced cell increases above the rest of the system. This is not an uncommon occurrence in a battery system but can cause stress on other cells in the system until the voltage equalizes.

Figure 9 - Screenshot of Historical Cell Voltage and Ohmic Value measurements

Proactive Maintenance

BMS data can be used to assist in proactive maintenance practices. As highlighted in this paper, real-time monitoring system data and daily historical trends provide significant insights into the operation of the battery system between Preventative Maintenance (PM) events. While certainly not a replacement for a battery PM, this data can provide battery technicians more information about how the battery is performing between routine maintenance and in some cases could provide enough evidence to extend a PM cycle.

With built-in graphing tools, or CSV output files, this data can often be sent to battery technicians automatically, by email, or locally accessed during a PM allowing technicians to identify failing cells within the system. Technicians could leverage this information to have replacement cells on-hand prior to arrival for the maintenance event reducing unnecessary downtime due to failed cells or units in the battery system.

Most importantly, the battery data from either battery monitoring or battery management systems must be regularly reviewed by trained individuals to make the best decisions on the battery system. Both systems perform well at monitoring and detecting battery issues, however it is often up to the user to work to resolve the issue within the battery system. Battery management systems will attempt to automatically resolve the issues within the battery system, or they will isolate the battery from operation, leaving the end-user vulnerable.

Conclusion

In conclusion, there are many options on the market when it comes to selecting a Battery Monitoring System (BMS). Those options may be even more limited when selecting advanced battery chemistries as a Battery Management System may be built-in and integrated directly into the battery cabinet itself. When used correctly, battery monitoring data can help users become proactive in identifying issues. This enables users to take swift steps to resolve the problem, helping ensure users get the most out of their battery investment. Each battery monitoring system has advantages and disadvantages depending on the use case, the battery chemistry, the size of the battery itself, and the design of the battery monitoring system itself. Reviewing the nuances and differences of available battery monitoring systems is outside the scope of this document. It is recommended that users take into consideration reliability, accuracy, accessibility, and serviceability of the systems they select.

As the demand for batteries continues to increase, one quickly realizes the solution to the growing industry isn’t one key technology or chemistry, but use of all available options. Equally important is understanding the health of each of these systems and the risk they impose to the application the batteries are used in. Improving reliability is not simply adding additional battery strings, the BMS is key in helping understand the health, reliability, and availability of these battery systems. Users should carefully consider the selection of the monitoring system and proactively monitor the data outputs to determine if action is needed to be taken to decrease impact to the customer load and increase the lifespan of their critical battery assets.

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