Joe Rocci
Walt Wilczewski
Phoenix Broadband Technologies
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Battery Connection Resistance

The Fear and the Science

Overview

Stationary battery plants are an essential component of most uninterruptible critical power systems. Of particular importance are battery plant runtime and battery plant safety under full load operating conditions. This is such an important matter that some critical infrastructure industries, such as electricity generating facilities, are now under federal regulation requiring them to monitor and report on the integrity of their backup battery systems. A key element in both runtime and safety is the integrity of the electrical connections that interconnect the individual cells in a string, as well as the inter-tier connections between blocks of cells. Poor or degrading connections can cause a range of performance and safety problems, including excessive voltage loss and dangerous heating conditions. Fearing the wrath of federal regulators, technical managers are consequently required to develop onerous compliance plans, with the hope that their plans hold up to scrutiny.

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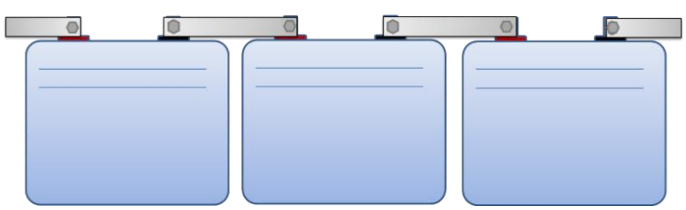
This paper addresses the subject of connection resistance in an analytical manner, hopefully allowing technical managers to avoid decision-making based on "fear & hope" and to instead make informed decisions based on logic and science. The examples shown are for flooded cells, but the basic principles apply equally to VRLA cells.

What Is Connection Resistance?

Battery power plants are typically comprised of "strings" of individual battery blocks ("cells") connected together with metal straps or cable/lug assemblies. A common configuration in the electric utility industry might consist of sixty 2 V flooded cells connected in series to provide a nominal 125 Vdc plant. A breakaway diagram of the interconnection between cells is shown below:



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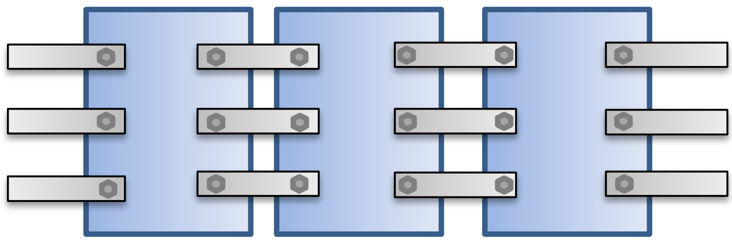
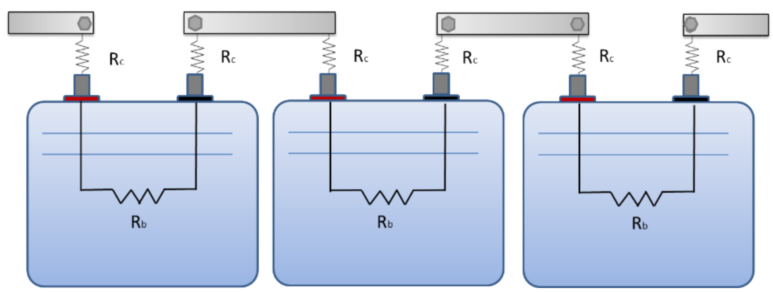
The cell type shown has two posts that are interconnected with adjacent cells using metal straps. These straps might be secured laying flat on top of the posts or horizontally on the side of the post, depending on the battery post design. In some cases, cable/lug assemblies are used in place of metal straps. In cases where larger capacity cells are employed, each cell might have multiple posts that are internally connected to provide lower inter-cell resistance and more even current distribution inside the cell. An example of a six-post cell is shown below:



In every case shown, the combination of the cell's internal resistance and its connection resistances forms a "loop" of resistances that gets multiplied by the number of cells in the string. A partial view of the loop resistances in a string of cells is shown below:



Each cell has an equivalent internal resistance (Rb) that is a function of non-idealities in the electrochemical process. This is a non-controllable parameter, which is nonlinearly and inversely proportional to the amp-hour capacity of the cell. For larger amp hour cells the resistance is typically in the range of 100 $\mu\Omega$ (micro-ohms) to 500 $\mu\Omega$ and as high as milli-ohms for multi-cell blocks. In addition, each cell has at least two connection resistances (Rc), one at each post/strap connection. In the case of multi-post cells, the load current will split into multiple paths entering the cell and recombine in multiple paths as the current exits the cell.

Connection resistance measurements are typically made at installation time, with a very sensitive instrument that can probe the battery post, as well as the strap, allowing individual connection resistances to be measured. IEEE standards 484 and 1187 suggest placing both instrument probes on the lead posts of adjacent cells. Note that this method essentially measures the total of the two connection resistances in a cell-cell path. Although not specified as an installation practice, individual connection resistances can be made by placing one meter probe on the strap near the cell post and the other meter probe directly on the lead cell post. This might be necessary when the strap is oriented horizontally on top of a very low-profile post, which blocks direct probe access to the post. In these cases, some discretion on the part of the installer is necessary, but all measurements should be made consistently for each cell in the string.

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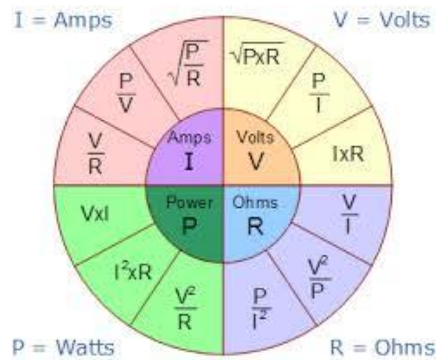
The world's most advanced battery monitoring system

Dimensioning the Issues

Cell connection resistance impacts battery performance in two major respects. Loose or corroded connections can cause heat to build and, if severe enough, could damage or destroy the cell post and/or cell internals. Degraded connections can also cause a voltage drop, which will diminish a battery's run time.

In the event of a discharge event, all of the load current will flow through the cell and connection resistances, with each resistance developing a corresponding voltage loss and a heat rise. Ohm's Law tells us that the voltage loss (Vr) through each resistance will be Vr = I x R. It also tells us that a heat source (Pr) will be developed at each resistance according to the magnitude Pr = I^2 x R. If we assume a typical load current of 100 A and a typical strap/post connection resistance of 20 $\mu\Omega$, we can calculate a voltage loss at each connection (assuming two-post cell) of Vr = 100 x 20^{-6} = 2 mV. With 60 cells and 120 connections, the total string voltage loss due to connection resistances is 120 x 2 mV = 240 mV or 0.2% of the total string voltage. The corresponding heat generated at a single connection is 100^2 x 20^{-6} = 0.2 W. Clearly, there is no problem at these current levels under "normal" conditions.



Again, using the case of a sixty (2 V) cell 125 V string, let's assume that each connection resistance has increased to 100 $\mu\Omega$, a 500% change. The total string voltage loss would increase to 1.2 V (1%) and the heat generated at each connection increases to 1 W. This is an absolute worst case situation where every connection has increased by 500%, and yet there are still no substantial performance or safety issues evident.

Now let's consider the case of a much bigger battery plant, capable of running at 1000 A loads and consisting of six-post cells as shown above. In this case, we can estimate that the load current splits equally into three (3) equal current paths entering the cell and recombines from three (3) equal current paths at the output. In this case, each connection is passing 333 A. For string-level voltage loss calculations, we can model this as 120 connections, each handling 333 A. Again assuming 20 $\mu\Omega$ connections, each connection loses Vr = 333 x 20^{-6} = 6.6 mV. This translates to about 0.8V loss or 0.6% at the string voltage level. Heat in each connection is 333^2 x 20^{-6} = 2.2 W, still an insignificant amount considering that it's absorbed by a heat sink with a thermal mass of many hundreds of pounds.

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What Does It All Mean?

The math clearly shows that the effect of connection degradations is trivial at the modest 100 A level, even if every connection in the string degraded 500%! The 1000 A load situation is very different, not so much because

of string voltage drop, but mostly because heat at any single connection increases as the square of the current flowing through the connection resistance ($P = I^2 \times R$). Consequently, for a given connection resistance, the heat at each connection is 100x greater for 1000 A than it is for 100 A. If the heat produced in a connection causes a substantial temperature rise, the lead post can soften, worsening the connection, which leads to higher resistance and higher temperature, and so on. The effect is another type of "thermal runaway" condition right at the connection, which could have catastrophic consequences. String voltage loss under full load is also a consideration but, as the math indicates, it would require modest connection degradation at every connection or a severe degradation at any single connection in order to substantially degrade string voltage.

Measuring vs. Monitoring Connection Resistance

The North American Electric Reliability Corporation (NERC), an international regulatory body that establishes standards for electric energy producers, has addressed many matters related to battery plant reliability in their standards document PRC-005-03. Among the many performance parameters regulated are inter-cell and inter-tier connections. The PRC document specifies that these parameters should be "verified" at 18-month intervals unless a system that "alarms and monitors" these connections is installed. The wording of the PRC is very vague and provides no specific values for connection resistance or how to "verify" them. Consequently, engineers have taken guidance from IEEE standards 484 and 1187. These documents offer extensive advice about connection resistance measurements related to initial commissioning of battery plants, but little in the way of "verifying" that the connections haven't changed significantly post-installation. The only dimensioned guidance offered by either standard is the allowed full load voltage drop at a single connection (20-30 mV) and the allowed change in cell-to-cell connection resistance from the installation baseline (+/- 20%).

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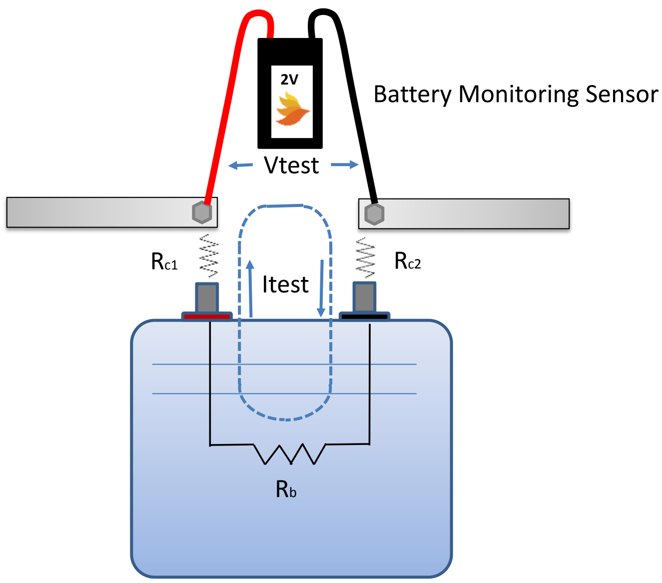
A Rational and Cost-Effective Monitoring Approach

When all is said and done, the goal of a test instrument is to provide the most accurate absolute measurement possible and the goal of a monitoring system is to detect performance changes that exceed some specified limits. As was pointed out earlier, the major monitoring considerations with respect to interconnection resistance are to verify that the total of all the resistances in the current loop will not cause an unacceptable drop in full load string voltage and that the rise in any single connection resistance will not develop sufficient heat under full load conditions to cause a dangerous heat situation. This can be accomplished by placement of the monitoring probes as shown below:



The illustration shows a sensor-based probe monitoring the cell and connection resistances. A wire-based probe can also be implemented at the same points with an attendant increase in installation complexity and reliability because the sensor-based system will have many fewer wires that need to be prepared and run back to the monitoring system control unit. In the case of the sensor-based probe, each probe forces a known AC test current (Itest) to flow through the cell loop-resistance consisting of Rc1, Rb and Rc2. The sensor measures the AC voltage (Vtest) developed as a result of this current and calculates a total block resistance equal to Rc1 + Rb + Rc2. Any change in any of these resistances that exceeds user-defined thresholds will cause a change in Vtest. If this change in loop resistance exceeds user-defined thresholds, an alarm will be indicated by the monitoring system at that location. Clearly, the integrity of every resistance in the test current loop, including the individual cell's internal resistance, is being monitored for changes, fulfilling the requirement of PRC-005-3 to "verify" the connection resistances. If a sensor is placed on every cell, it can be shown that every connection in the string, including inter-tier connections, is being monitored for integrity. Further, the 484 and 1187 documents are meter-centric and don't address the concessions that have to be made in order to continually monitor the most important parameters related to performance and safety. With a meter, it is very easy (albeit tedious) to measure and record each of the more than 360 connections in a string of sixty (60) six-post cells. An equivalent monitoring system would require 360 sensing connections if it were at all technically and economically feasible to produce a system that can monitor this many independent connections! It isn't. Consequently, monitoring system suppliers have to pick and choose which connections are critical and should be probed and which connections don't require continual monitoring. Some can monitor inter-tier connections and some even monitor inter-cell connections, but none can measure every connection on every cell. Consequently, users of battery monitoring system must choose which resistance measurement points are meaningful to fulfilling the requirement of the law to "verify" cell-to-cell connection resistance and which ones just contribute to "data overload", system complexity and unreliability.

"An equivalent monitoring system would require 360 sensing connections if it were at all technically and economically feasible to produce a system that can monitor this many independent connections!'

Recommended Compliance Practices

The objectives of PRC-005-03 can be met by establishing a connection resistance "baseline" with a calibrated meter at battery plant installation time. Records should be kept of each measured resistance, adhering to the methods outlined in IEEE standards 484 and 1187 as closely as practical. Thereafter, a properly installed battery monitoring system with probes attached to each cell's input and output connection points will provide monitoring of not only changes in the cell's internal resistance, but also changes in the connections from cell to cell, as well as from tier to tier, thus fulfilling the requirement to "verify" connection integrity in an ongoing maintenance program. If subsequent replacement of individual cells is necessary, or if any connections are loosened, tightened, removed or replaced, a new baseline should be made with a meter and the monitoring system's baselines should be updated accordingly.

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Conclusions

- Degradation in cell-to-cell connection resistances can cause a drop in string voltage and a heat rise at each connection under full load conditions.
- Heat rise, if large enough, can cause a dangerous thermal runaway right at the connection.
- With typical 100 A utility substation loads, connection resistance is far less of a problem than at locations where the load current can be 1000 A or more.
- At the 1000 A load level, the major problem caused by a moderately degraded single connection will be heat buildup at the point of the degraded connection. A multiplicity of moderately degraded connections could adversely affect string voltage under full load, but this is statistically less likely than the single connection degradation.
- PRC-005-03 requires that each cell-to-cell connection be "verified" for changes from an installation baseline.
- IEEE standards 484 and 1187 offer manual methods to establish the baseline at installation time, but little in the way of guidance for ongoing monitoring.
- A properly installed battery monitoring system that monitors each cell's composite internal and connection loop resistance can be used to fulfill the PRC-005-03 requirement to "verify" connection resistances.

"A properly installed battery monitoring system that monitors each cell's composite internal and connection loop resistance can be used to fulfill the PRC-005-03 requirement to "verify" connection resistances."