Thermal Runaway in UPS Batteries

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Diagnosing Thermal Runaway

About ten years ago, one of my clients asked me to look into a UPS battery failure scenario. This client had three UPS systems that were paralleled in a systems cabinet. There was a string of wet cell batteries for each UPS system. All three strings were in a single room. Two of the strings were back-to-back on a common battery rack. The third string was separated from the other two by a four-foot aisle. Other than the batteries and the disconnect switches, and some convenience lighting and outlets, there is no other equipment in the room.

When I was at the site, the room temperature was about 70-74°F with conditioned air. There were exhaust registers that operated through an exhaust fan outside of the space

The failure consisted of the two strings that were located on the common rack. All the batteries on this rack showed partially deformed jars due to a high heat condition. The electrolyte level in the jars was anywhere from near empty to 60 percent full, there was a white residue on the tops of the jars and the racks, and the grease on many of the terminals was melted. The remaining battery string on the adjacent rack appeared to be in excellent condition and was not affected by the failure.

Based on the condition of the failed batteries, a situation known as "thermal runaway" probably occurred. Thermal runaway is a phenomenon whereby the temperature and chemical conditions within a battery jar generate heat faster than it can be dissipated. The pre-thermal runaway phase of this failure relies on the voltage and current from the charger to generate the heat. After a while and under the right conditions, the battery becomes a self-sustaining reaction and generates its own heat regardless of whether or not there is an external voltage on the terminals. The battery then boils on its own until there is so little water remaining that the oxidizing reaction tapers off and the battery is non-conductive. This failure then spreads to the remaining cells in the string due to a higher charging voltage across the remaining cells, as well as the high temperatures of the batteries that are adjacent to the battery that is in thermal runaway. The entire string of batteries will eventually boil away the electrolyte. The heat from the failed string most likely caused a cascade failure of the adjacent battery string that was located on the same rack. The undamaged string that remained in the room was not subjected to the high heat conditions due to the physical distance of the aisle from the failed strings.

Runaway in Practice and Theory

To illustrate the reason why thermal runaway propagates to all the cells in a string, I want to offer the following example: A conventional lead-acid battery delivers 2.2 volts per cell. Under normal float charging, the charging voltage is set at about 2.3 volts per cell. If there were 100 cells in a battery string, the charger would be set up for 230 volts. If each jar contains 6 cells, which is common, each jar would have about 13.8 volts across its terminals. If one jar failed due to shorted plates, the overall charger voltage would remain at 230 volts, however the number of cells would be reduced to 94, thus the voltage across each cell would now be 2.45 volts. If two jars were shorted, the voltage across each cell would increase to

2.61 volts. At 2.61 volts for a period of hours, the battery plate temperature would rise to the point where thermal runaway would occur. As the electrolyte in each battery boils away, the remaining batteries would be impressed with higher and higher voltages. The temperature of those batteries would rise due to the higher voltage, and also due to the high heat that is being conducted from adjacent failed batteries, and eventually the entire string would fail. Adjacent batteries would go into thermal runaway due to the heating of adjacent strings, and then be aggravated by the voltage rise of their own chargers. If the batteries were not properly vented, the jars would explode.

When the electrolyte boils, large quantities of hydrogen sulfide and sulfur dioxide gases are given off which are toxic. Various sulfate compounds are deposited on the cells after the water has evaporated and is typically a white or off-white residue. Very little hydrogen gas is given off during a thermal runaway failure.

As to the root of the situation, anything that raises the cell temperature to that critical level can initiate thermal runaway. Typical causes may be any or a combination of the following:

Room temperature was higher than 77 degrees F. Battery chargers are set to deliver a constant float voltage of 2.3 volts per cell, which is an industry standard based on an ambient space temperature of 77 degrees. If the room temperature is higher than 77 degrees, the batteries will overcharge and the plate temperature will rise. Float voltage must be reduced. Electrolyte will evaporate faster, levels may drop quicker than can be recognized in routine inspections. As the wetted surface areas of the plates are reduced, the temperature of the cells begins to rise exponentially.

Incorrectly set voltage levels on the charger. If the voltage level is higher than 2.3 volts per cell, and the room temperature is normal, the batteries will be warm, thus raising the evaporation rate of the electrolyte. The ultimate result is the same as in the previous example.

Shorted cells due to manufacturer's defects. Poor quality control during the manufacture of the batteries can lead to prematurely shorted cells. When a cell short-circuits, there is a large flow of charge between the positive and negative plates of the cell, the plate temperature will rapidly rise and the overall temperature of the cell may rise to the point of thermal runaway. Even if the runaway did not occur during the short, the remaining cells will then see a higher volts-per-cell which will raise the rate of electrolyte evaporation, thus raising "normal" internal jar temperatures.

Shorted cells due to aging, excessive load cycling, lack of maintenance, etc. Battery cells can short circuit for a variety of reasons. As batteries are charged, conductive deposits fall off the plates and settle to the bottom of the jars. As the sediment builds, it will eventually rise to the level of the plates and short the plates. Wet cell batteries are typically pro-rated for 20 years, but the reality is that battery life is a function of the number of discharge cycles. If a battery in a UPS string is frequently called upon to deliver power to a load, its useful life will be much less than twenty years. The sediment level is a good indication of the aging of a battery. Similarly, a poorly maintained battery will be more fully discharged and then excessively recharged which hastens its death due to sediment buildup.

Lack of consistency in the relative condition or age of the jars. As batteries age, their internal impedance rises, and they will then require more current to maintain the nominal 2.3 float voltage. The resulting current is consistent through every cell of every battery in the string. If a single brand new jar were installed as a replacement in an older string, for example, that jar would have much lower impedance than the remaining batteries in the string. The voltage across its terminals would be proportionally lower than the other batteries in the string, and the cell temperature of the older batteries would be higher due to overcharging.

Monitoring: an Ounce of Prevention

Because this installation did not have a monitoring system in place, it may be impossible to determine the exact cause of the initiation of the failure. Battery monitoring systems record the voltage and temperature of every jar and the data can be saved and reviewed to establish trends. If a particular jar has abnormal conditions, it can be isolated and replaced well in advance of thermal runaway. Laboratory tests by battery vendors have shown that it takes hours or days for thermal runaway to be self-sustaining.

There are a host of vendors that offer sophisticated monitoring systems for UPS batteries. Obviously, the critical nature of UPS loads may warrant the use of such systems, especially in wet-cell installations where the initial cost of the batteries is high and maximum battery life is warranted. However, thermal runaway is historically more common in VRLA battery strings than in traditional wet-cell installations, so any critical lead-acid battery installation may be a candidate for monitoring.

VRLA batteries have a typical pro-rated life of 10 years, but most, if not all UPS vendors recommend a complete replacement of the batteries after 5 years to be safe. The reason for this is that they recognize the claim that "maintenance-free" is often interpreted by most customers to mean "out-of-sight-out-of-mind." In fact, other than the refilling of the cells with water, regular maintenance consisting of physical inspections, cleaning of terminals, checking of voltage and temperature, etc. is still required and necessary. A battery monitoring system for cells is almost a necessity to squeeze the maximum life from any battery string. Replacing VRLA cells after 5 years is safe alternative.

Would a hydrogen gas sensor have prevented this problem? Hydrogen gas detection is not required by code and is nearly worthless in any battery installation. It is valid to make the point that hydrogen gas may build up on the underside of a concrete coffered ceiling construction to the point where it may be explosive. This assumes excessive overcharging of the batteries, which are venting excess hydrogen gas. If you were lucky enough to place your gas detector in the correct coffer, it may notify someone that a potentially dangerous condition exists. Otherwise it will never detect anything and will be an expensive system that needs periodic testing, calibration, and maintenance. In a building with steel deck construction and numerous ventilation openings, a hydrogen gas detection system will rarely if ever go into alarm due to the scores or leaks and openings in the deck structure.

Vendors for battery installations also offer hydrogen sulfide and sulfur dioxide gas detection systems. My view on the need for these systems is about the same as that for hydrogen gas. If these systems go into alarm, the thermal runaway condition has already started and there is nothing that can curtail it. Evacuation is the only measure that can be implemented at that point in time. As I mentioned, it takes hours or days of abnormal conditions to trigger a thermal runaway event. A better solution is to have a voltage and temperature monitoring system in place, or to undertake periodic inspections by qualified technician. Does the room have a peculiar odor? Are the room fans running? Are any of the jars warm to the touch? Do the battery terminals or the tops of the jars have deposits on them? Is there any melted grease? Is the level of charger current reasonable and consistent with records? All these questions must be answered during periodic inspections of battery plants, including "maintenance-free" VRLA battery installations.

Thermal runaway is a rare occurrence that can evolve into a real disaster, but with good maintenance and regular inspection routines, the likelihood of it ever happening is slim. A battery monitoring system goes a long way in an installation having many batteries, but there is still no substitute for a good set of eyes and ears on the ground.

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