Prevention Through Design, Strategies To Reduce The Hazards Of Stationary Battery Systems Through Intelligent Design

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Michael P. O'Brien
Senior Member, IEEE
Exponential Power
21448 Marion Lane
Mandeville, LA 70471
USA
mike.obrien@exponentialpower.com

John R. Todora
Exponential Power
207 Deerwood Glen Dr.
Deer Park, TX 77536
USA
john.todora@ exponentialpower.com

Abstract – Stationary Battery Systems provide the control and reserve power for modern life as we know it. These systems provide control power for switchgear and automated controls, the power for field flashing of generators, emergency lube oil and seal oil pumps and other critical motors, the reserve power for UPS systems, and the operating power for critical communication systems. In short these battery systems make modern life possible, and they surround us.

Stationary Battery Systems present unique maintenance hazards due to the availability of high currents, lethal voltages, flammable/explosive gas, and corrosive chemicals.

All work on stationary batteries is energized work. This paper will show that we can make the stationary battery systems safer today by implementing a few well thought out, yet simple and low-cost system design changes that reduce the potential for injury and death while ensuring that the battery system can be safely maintained throughout its service life.

Another major concern addressed in the paper is the designing of simple protection devices that guard against Human Performance failings. "Things Happen". By learning from experience, we can provide simple design changes that reduce the potential of things like short circuits caused by dropped wrenches. We will also address the need to guard against fixing one problem only to inadvertently produce another.

Prevention through Design for Stationary batteries…Its time has come, and it's about time!

Index Terms — Stationary Battery Systems.

I. INTRODUCTION

Stationary battery systems have a high potential for electrical risk but with proper forethought and the implementation of simple design features, we can reduce that risk. This paper discusses simple but often overlooked or misapplied methods of improving the safety of stationary battery systems, or Prevention through Design, (PtD), applied to stationary battery systems. Stationary battery systems are traditionally used in telecommunications, industrial control systems, switchgear systems, (MCC, substation, and generating station), and UPS applications. The batteries in these systems are on constant float charge and only discharge in an emergency or unusual event. These DC systems are typically designed in accordance with IEEE standards 484, 1106, 1187, 1184, 1375, and 946, and maintained in accordance with IEEE standards 450, 1106, 1184, and 1188. This paper does not address cyclic applications such as photovoltaic systems or Bulk Energy Storage Systems, (BESS), although designers of these systems may find some of the items discussed in the paper desirable for their systems.

II. DEFINITION

A stationary battery is a collection of cells connected in series that when properly designed, installed, and maintained will never fail to support the connected load. It is a highly reliable source of standby power. It is available when no other power source is available. It is always replaced while still capable of supporting the connected load, and, the cost of a stationary battery failing to support its connected load under worst case conditions can easily reach into the millions of dollars. These systems require regular maintenance and periodic testing to ensure they can support the connected load and to determine timely replacement. These activities place workers at risk of hazards that they can easily be protected from through proper stationary battery system design practices. .

III. THE HAZARDS

Stationary battery systems present the following hazards:

1) *Shock Hazard:* Each cell in a battery is an electrochemical power supply. Once the cell is manufactured and activated it cannot normally be de-energized; therefore all work on a battery is energized work. This is true even when the voltage level is below what industry considers a safe level. As cells are connected in series the shock hazard and arc flash incident energy increases and the hazard to maintenance technicians increases.

2) *Arc Flash:* The cells used in stationary batteries can typically deliver short circuit currents from a few hundred amps to over 30,000 amps. A short circuit hazard exists even when no shock hazard exists. Battery arc flash

incident energy calculations are still a developing science and thus much remains to be learned. Testing performed by Bonneville Power Administration in 2017 and Hydro-Quebec in 2018 show that incident energies are low at 100-140VDC systems. However, the Hydro-Quebec testing showed that incident energies more than quadrupled at 260VDC and quadrupled again at 500VDC. Additionally, Hydro-Quebec's testing showed that arc times at 500VDC can exceed 2-seconds. Their testing stopped at 2-seconds but all their 500VDC tests achieved arc times of 2-seconds. Those arcs ended at 2-seconds because the test ended, not because the arc self-extinguished. This indicates that incident energies for 500VDC batteries may be significantly more than previously estimated.

3) *Corrosive Liquids:* The electrolytes used in stationary batteries are dilute sulfuric acid for Vented Lead Acid, (VLA), and Valve Regulated Lead Acid, (VRLA), cells and dilute potassium hydroxide for Nickel Cadmium, (NiCd), cells. Both chemicals are corrosive to human tissue especially the eyes and mucus membranes.

4) *Flammable/Explosive Gas:* VLA, VRLA, and NiCd cells produce a highly explosive mixture of hydrogen and oxygen gasses. This gas is vented to the atmosphere. VRLA cells typically vent significantly less hydrogen to the atmosphere but this emission must still be considered in the battery system design.

5) *Thermal Runaway:* VLA, VRLA, and NiCd cells require an external energy source, (battery charger), to enter thermal runaway. The DC system should be designed to prevent thermal runaway from occurring.

6) *Weight:* The smallest cells used in stationary batteries typically weight approximately 20 lbs. while the largest cells can weigh in access of 700 lbs. The weight of some VRLA modules can exceed 900 lbs. The weight of cells used in stationary batteries is normally only a hazard during installation, individual cell/module replacement, and at end-of-life replacement.

IV. DESIGN CONSIDERATIONS

Most DC systems have more than one load and therefore should have a main DC panel. This should normally be the center point of the DC system. All DC power sources, battery or batteries and all chargers should feed into the main DC panel. All loads should feed out from the main DC panel. Such designs allow major components of the DC system to be repaired or replaced without performing energized work. The battery or batteries and the chargers will likely be replaced during the operational life of this DC system; therefore the charger output terminals or the positive and negative battery terminals should never be the center tie or connection point for the DC system.

Temporary Battery Connection: The DC system should have a mechanism for connecting a full size temporary battery without working on energized terminals. All stationary batteries will require removal from service for capacity testing, replacement, and potentially for remedial maintenance. The load equipment connected to most stationary battery DC systems cannot be safely operated without the battery connected. For example, the DC system of a substation or MCC switchgear can only be safely de-energized when the switchgear is totally de-energized. The typical stationary battery charger is not capable of supporting switchgear circuit breaker operation without a battery connected. Even if the charger had the capacity and response time to support switchgear circuit breaker operation one must also assume that the power to the charger would be adversely affected by the fault responsible for the circuit breaker operation and thus the charger would not have the input energy needed to support the switchgear circuit breaker operation.

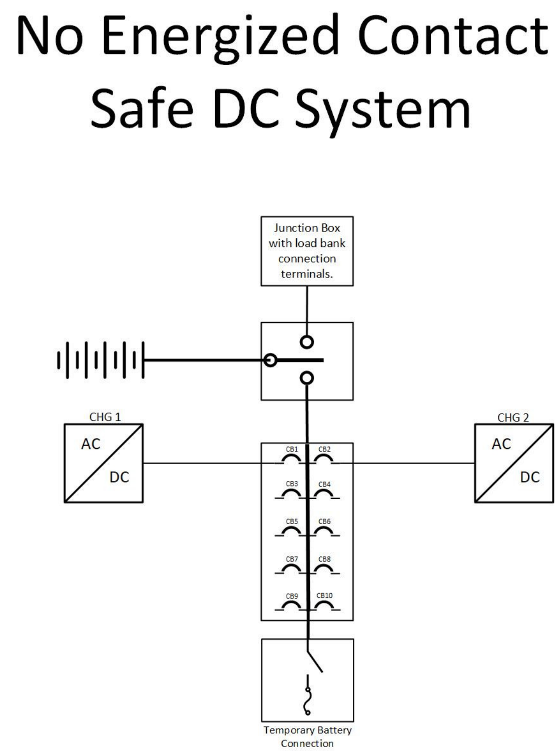

Fig 1. Safe DC System

System Voltage: The voltage of the battery and DC system should be as low as practical. System voltages above 140VDC should be carefully considered. System voltages approaching 500VDC should be avoided if possible. Reducing the DC system voltage to the lowest practical value reduce both the electrical shock hazard and the arc flash hazard. DC system voltages at or below 150VDC have substantially reduced arc flash incident energies.

System Grounding: With the exception of telecommunications systems, stationary battery DC systems are intentionally isolated from earth ground. This is totally opposite of the AC world which is always referenced to earth ground. The rationale behind isolating DC systems from earth ground is that these critical systems must always be capable of supporting their connected load even in the event of foreseeable problems. A single ground fault on the load side of the DC system is a foreseeable event. An ungrounded DC system allows the load to remain in service. All intentionally ungrounded DC systems should have an active ground fault detection circuit. This active ground fault detection circuit is often located in the battery charger, but it could be elsewhere on the DC system. UPS battery systems should not be referenced to earth ground. Ungrounded DC systems are a safety plus and a potential hazard. The plus is that with no reference to earth ground there is no shock hazard if a technician touches any single terminal in the battery or single polarity in the DC system. The potential hazard is that when a ground fault develops the DC system is now referenced to earth ground and all ungrounded parts of the DC system now present a shock hazard. Maintenance technicians can become complacent assuming that the DC system is always ungrounded. Conductive battery racks must still be bonded to the building ground system.

Cell Mounting: VLA and NiCd cells are typically mounted on open racks which allow easy access to the individual cells or jars. Multi-tier racks are preferred over Step racks as Step racks require maintenance technicians to lean over the energized intercell connections on the front step to reach the cells on second and subsequent steps. Cell replacement is also far more difficult on Step rack verses multi-tier racks.

Fig 2, 2-Tier 2-Step Rack

Multi-tier racks should have side and end rails to prevent the cells from being accidentally knocked off the rack. This has happened and it's an easily foreseeable hazard that can easily be eliminated.

Small VRLA cells typically use mono-block construction and are not a good choice for stationary battery applications due to their relatively short life and unpredictability. However, mono-block VRLA cell types are common in UPS and smaller telecommunications applications and are also used in some MCC and substation switchgear applications. The VRLA mono-blocks are sometimes placed on open racks but are often placed into cabinets. Many UPS systems use battery voltages in excess of 150VDC and then place VRLA mono-block jars into battery cabinets. Battery cabinets should be avoided especially when DC system voltages exceed 150VDC.

All VLA, NiCd, and VRLA mono-block jars should have electrolyte resistant insulating material between the jars and any conductive rack member. This requirement is a standard part of IEEE standards 484 and 1106 for VLA and NiCd cells, but it is not included in 1187 for VRLA cells. This insulation helps to prevent an accidental ground fault from developing due to an electrolyte leak.

Large VRLA cells are typically mounted in steel modules which bolt together to form a battery rack or steel cans that then bolt into a steel rack. These VRLA cells are normally mounted horizontally. This places all the cell posts/terminals facing maintenance technicians.

Spill Containment: IEEE Standard 1578-2018 covers spill containment. Spill containment floor dams should be easily removable to facilitate cell and battery replacement. Stationary cells are often moved using hydraulic lift tables. These lifting devices need be very close to the battery rack when installing or removing a cell. Spill containment floor dams that cannot be easily removed and reinstalled present an additional hazard by preventing the lifting equipment from getting close enough to the battery rack.

V. ADDRESSING THE SPECIFIC HAZARDS

Eliminating or minimizing hazards often has unintended consequences which can negatively impact battery reserve time, reliability, maintenance, and sometimes all three at once. It is possible to design a system that is so safe that it is unusable. It is the designer's responsibility to select the best mitigation strategy for their respective DC system.

When selecting mitigation strategies the designer should be very concerned with cable and switch induced voltage loss. The AC world often is unconcerned with cable losses; however, the DC world should be paranoid about them. Battery cabling should always be sized for minimum voltage drop. Such cable sizing will provide plenty of ampacity. Cable losses in stationary battery systems can cause significant reductions in battery reserve time or substantial increases in system costs.

VI. ELECTRIC SHOCK HAZARDS

The greatest shock hazard is at the positive and negative battery terminals. Ideally, these terminals should be physically as far apart as possible and should also have easily removable clear insulating covers. While this sounds easy, the execution can be problematic. For instance a 60-cell VLA or 92-Cell NiCd installed on a 2-tier rack will normally have the positive and negative battery terminals at the same end of the rack. The battery manufacturer would normally supply a properly sized intertier cable connection which would be placed between cells 30-31 on the 60-cell VLA battery or between cells 46-47 on the 92-Cell NiCd battery. On smaller batteries it is feasible to run a large long cable or cables from one end of the battery rack to other to facilitate placing the positive and negative battery terminals at opposite ends of the battery rack. On larger batteries this long cable may not be feasible. Remember, this cable will have voltage loss under load which must be accounted for in the sizing of the battery.

Placing the positive and negative battery terminals as far apart as possible also reduces the arc flash hazard. Arc flash incident energy is greatest ay the battery terminals. The farther apart the terminal are the less likelihood a technician can short circuit the battery. This also reduces the voltage a technician is exposed to during maintenance.

Insulating Covers: All connections within the battery, (intercell, interjar, intertier, inter-row and the positive and negative battery terminals), should be covered with clear easily removable insulating covers. Additionally these insulating covers should provide easy access for voltage measurements without removing the covers. The insulating cover must be clear to permit easy inspection of the connections for corrosion. Additionally, clear insulating covers should be sectionalized so that the removal of a single cover does not expose more energized terminals than necessary for the work being performed. The proper use of clear insulating covers can satisfy NFPA 70E Article 320.3(A)(1)(2).

Insulated intercell connectors are discouraged because they can hide corrosion. Additionally, some models so insulate the cell posts that connection resistance measurements are impossible to obtain. Totally insulated intercell connections may make the battery electrically safer, but the unintended consequence is an unmaintainable battery.

Input Transformers: All chargers/rectifiers on stationary battery systems should always have an input transformer before the rectifier semiconductors. Many UPS systems and some chargers do not have an input transformer. The lack of an input transformer provides a ground reference to the battery. This typically results in ½ battery voltage between earth ground and the positive or negative battery terminal and may also impress a lethal AC voltage on the battery.

Sectionalizing the Battery: Electrically separating a battery into low voltage sections for maintenance is strongly discouraged for most stationary battery systems. The IEEE stationary battery maintenance standards, 450, 1106, and 1188 all recommend that normal maintenance or inspections be conducted with the battery under float charge which is the normal operating mode for stationary batteries. Sectionalizing the battery significantly reduces the effectiveness of maintenance program. Sectionalizing a battery can introduce significant cable and switch induced voltage losses which must be accounted for in battery sizing. Sectionalizing may be desirable in 250-500VDC batteries in cabinets, but a better solution would be to use a lower voltage DC system and place the battery on an open rack.

VII. ARC FLASH HAZARDS

Battery arc flash calculations are a developing science. Testing conducted by Bonneville Power Administration in 2017 and Hydro-Quebec in 2018 show that category 2 arc flash PPE can provide adequate protection at voltages up to 140VDC. Higher battery voltages produce substantially more arc flash incident energy. The use of battery voltages above 140VDC should be carefully considered and potentially discouraged especially when battery voltages approach or exceed 500VDC. When a higher voltage battery is a necessity, a properly sized current limiting center-point fuse should be used to limit arc flash incident energy.

VIII. CORROSIVE LIQUID HAZARD

Corrosive liquid spills are best handled by proper maintenance practices and by complying with the spill containment and management recommendations described in IEEE Std. 1578-2018 - Recommended Practice for Stationary Battery Electrolyte Spill Containment and Management. Chemical PPE should always be properly worn when working with battery electrolyte. Chemical PPE is not required for many battery maintenance activities, see NFPA 70E-2018 Article 320.3(B)(2).

IX. FLAMMABLE/EXPLOSIVE GAS HAZARD

Ventilation: Stationary battery rooms/enclosures must be ventilated. The ventilation system should comply with IEEE Standard 1635. Additionally, a permanently installed hydrogen detector should be integrated into the building or enclosure alarm system.

Flame Arrestors: All stationary battery cells should be equipped with a flame arrestor to prevent ignition sources from igniting the hydrogen within each cell, see NFPA 70E Article 320.3(C)(2)(D). The flame arrestors for VLA and NiCd cells should be equipped with a funnel with a stem extending well below the low electrolyte level line. This allows access to the electrolyte without violating the protection offered by the flame arrestor.

Manifold Vent Systems: Manifold vent systems are ventilation systems where the vent of each cell is connected together through a manifold system and the hydrogen and oxygen gases are collected and vented outside the building or enclosure.

Fig 3. Manifold Vent System

The use of such systems is very strongly discouraged as a single ignition source can ignite the hydrogen in every cell, much like a string of fire crackers. Additionally, the atmosphere in the manifold system is always an explosive mixture of hydrogen and oxygen. What was intended to make the battery room/enclosure safer actually makes it more dangerous and reduces the reliability of the battery and DC system.

X. THERMAL RUNAWAY HAZARD

Unlike lithium chemistries, VLA, VRLA, and NiCd cells do not contain enough energy to enter a thermal runaway condition without an external energy source. The external energy source is the charger(s). Using a temperature compensating charger with an external temperature probe sensing battery temperature will prevent thermal runaway in a VLA, VRLA, and NiCd battery. When an internal fault causes the temperature of the battery to increase the temperature compensation circuit will reduce the charge voltage to the battery thus reducing the charge current to the battery effectively arresting the thermal runaway condition before it gains traction.

An unbalanced oxygen recombination reaction can occur in VRLA cells which can lead to thermal runaway. When this occurs in a single cell the cell will fail, but when this condition occurs in just 10-12% of the cells within a given battery the entire battery can begin the march toward thermal runaway.

VLA and NiCd batteries typically require significant internal shorting of 10-12% of the cells within a given battery or a runaway charger to enter thermal runaway. A temperature compensating charger with an external temperature probe sensing battery temperature will prevent or arrest thermal runaway in a VLA, VRLA, and NiCd battery under virtually all conditions except charger runaway.

XI. CONCLUSIONS

Stationary Battery Systems are essential to life as we live it today. The challenge is to ensure that these energized systems, with the potential to cause harm, are as safe as possible to work on and around. We ask our maintenance teams and others to do so every day. As managers, engineers, and safety professionals it is not only our challenge; it is our responsibility to make stationary battery systems as safe as possible.

As this paper has shown, improving the safety of stationary battery systems does not involve major capital expenditures or a drain on already over-taxed manpower. It only requires applying proactive forethought and common sense around the inherent battery hazards described above. Prevention through Design is a proactive approach to reduce the potential harm and guard against the complacency that is part of Human Performance failings.

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XIII. VITAE

Michael (Mike) P. O’Brien (IEEE Senior Member) - Mike is a veteran of the USAF and has over 40 years of experience in the electrical field. He has served as a consultant to HQ Air Force Communication Command on high reliability power systems where he authored a regulation on Stationary Battery Maintenance and Testing and a technical manual on a military version of a UPS used in Critical Command & Communications power systems.

After leaving consulting he was employed by Alber Engineering Inc where he assisted in the design and marketing of battery capacity test equipment, battery monitoring systems, and developed and taught training programs on stationary battery systems.

Mike has been with Nolan Power Group, now Exponential Power, for the past 29 years where he is the Technical Services Manager. He has written a number of technical papers on stationary battery systems and testing and has been a panel member at several technical conferences. Mike is the senior technical expert at the combined companies of SBS/NPG/QSS. He is also a senior instructor at the Battery Academy and a voting member of the IEEE standards association.

John R. Todora has been in industrial sales for 37-years. The last 17 have been with Nolan Power Group, now Exponential Power, working with customers, helping them to better understand their standby power systems.

Teaching as a first career led John to a desire to help customers through better communication of needs and the development of appropriate solutions. Since joining Nolan Power Group in 2004, he has worked with a number of large battery system owners throughout the Gulf Coast region in all markets including large power plants, industrial and chemical plants, and data centers who all share the same basic battery needs for safe, reliable DC power systems that support their operations when called on.