REDUCING RISK IN THE DESIGN OF BATTERIES

David Rosewater
Grid Energy Storage Researcher
Sandia National Laboratories
Albuquerque, New Mexico

Abstract
Design guidance for batteries in the national electrical code [11] can be substantially improved. Article 480, storage batteries was developed around the work practices in NFPA 70E, which does not currently contain requirements for battery sectionalization procedures. This has led to some rules that don't make sense for batteries and a lack of many of the best practices that have been developed for the design and construction of safer battery systems. The principles of the control of hazardous energy, including lockout tagout, can and need to be adapted to the design of batteries. A safer battery design can enable workers to establish a lower-risk work condition by sectionalizing the battery into lower voltage and/or lower energy segments. This paper explores how battery design changes can impact worker safety. The paper also covers how common engineering controls, like breakers and terminal covers, affect the battery risk assessment required by NFPA 70E. Lastly, the paper presents a list of changes proposed to the national electrical code that clarify a minimum set of requirements for storage batteries that would reduce risk and protect workers.

Introduction
The battery energy storage industry is undergoing transformative growth. Projections vary, but even conservative estimates have the per-year installation of energy storage systems, of which batteries make up almost all, growing by more than an order of magnitude in the coming decade [1]. This will require a substantial increase in the labor force of technicians and electricians working on and around battery systems. Unfortunately, this is also likely to incur many injuries as inexperienced workers interact with energized batteries. As the cost of batteries falls, the cost of installation and maintenance will rise as a fraction of the overall cost of a battery system. There will be pressure on workers to move quickly and take shortcuts to reduce these costs. Both worker safety concerns and installation time pressures can be addressed through design.

Recent work has focused on battery electrical safety in the workplace [2], including for field service technicians [3] and in repairing electrical vehicles [4]. Battery electrical hazards are divided into shock, arc flash, and thermal. Each hazard is assessed by the worker, sometimes by reading equipment hazard labels prepared by the designer, and controlled through their procedures and PPE. However, procedures and PPE are downstream of and less effective than engineering controls implemented in the design of a battery system [10]. Electrical vehicle manufacturers, for example, identify specific test points for verifying zero energy on the battery terminals during repairs [4]. A poorly designed battery system will expose workers to unnecessarily high electrical hazards. Code requirements for storage batteries logically focus on the potential fire hazard with requirements for size and separation, energy management, fire suppression, and gas detection [12,13]. Spill control for hazardous electrolyte is also included [13]. Comparatively little guidance is provided on battery electrical safety design.

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This paper explores the electrical hazards present in storage battery systems. Each hazard is assessed in detail to identify effective methods of control. An electrically safer battery design is then proposed that reduces risk to workers performing installation, maintenance, testing, and removal of battery systems. Lastly, this paper offers specific draft changes to the US national electrical code (NEC) [11]. These draft changes would hold designers responsible for making battery systems that can be worked on safely. Including these draft changes is intended to start a productive conversation that will lead to a collective push for common sense changes in the code.

A Closer Look at Battery Electrical Hazards

There is a pervasive assumption in the analysis of battery hazards that impacts both our work procedures and the physical design systems. In facility ac and dc power circuits positive and negative voltages are kept close together for many reasons including for reduced cost and footprint. Because of this, electrical hazard analysis tends to implicitly assume that exposed electrical conductors will be close together (e.g. in a panel), even in systems where they are not. In design, engineers will often arrange conductors to be close together for convenience and by convention, even if it would be safer to keep them far apart. They do this, in part, because the current electrical safety standards do not appropriately credit designers for conductor spacing in hazard analysis. This section is intended to adapt and extend shock, arc flash, and thermal hazard analysis to include the impact of conductor spacing. Note that large circuits conducting high current can have significant magnetic effects so circuit designs should balance safety requirements with electromagnetic compatibility.

DC Shock Hazard

Batteries cannot be deenergized. A common design method to reduce the risk of a shock is to operate the battery in an ungrounded state as is permitted by NEC 480.13 [11] if there is ground fault detection and indication. In ungrounded stationary battery systems dc voltage that could cause shock can be physically separated farther than twice the limited approach boundary. This means that if someone reached out in both directions, they could not span a hazardous battery voltage above 100 V, as specified in article 320 of NFPA 70E [6]. Figure 1 shows three examples of limited approach boundaries (LAB) for a 200 V battery string. If the exposed conductors are more than 7' apart then there is no path for current to travel through the human body and hence an extremely low shock hazard.

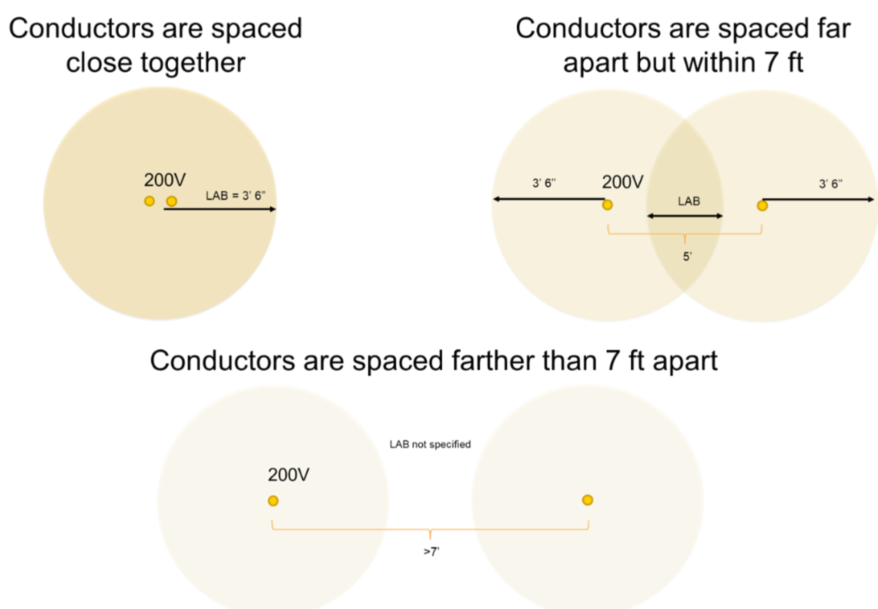


Figure 1. Limited Approach Boundary (LAB) based on high conductor spacing.

For example, a string of vented lead-acid cells connected in series to build a 125 V standby battery, arranged on a 1-step rack, can require 30’ (10 m) or more of length. This means that the maximum voltage within 7’ (2 m), twice the LAB distance from [6] of 3’ 6’’ (1 m), is approximately 28 V dc. There is extremely low risk of a shock in such a battery system because the maximum voltage that the worker could be exposed to is below the dc shock threshold. Figure 2 shows how the restricted approach boundary changes depending on the location of the worker. This is because a worker that is completely outside the LAB cannot bridge a hazardous battery voltage.

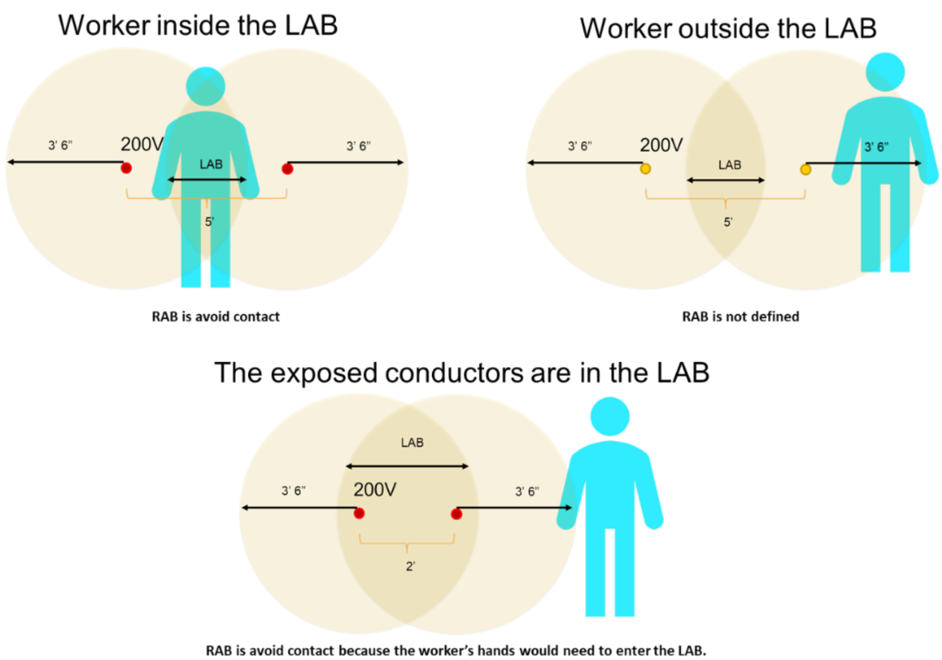


Figure 2. Restricted Approach Boundary (RAB) based on high conductor spacing.

Shock Hazard in a Non-Isolated Uninterruptable Power Supplies

An important caveat to the discussion above is the case of non-isolated uninterruptable power supplies (UPS). These UPS systems do not include an isolation transformer, instead connecting directly to the grounded wye utility transformer. Non-isolated UPS are becoming more common as they have slightly lower cost and higher efficiency then isolated UPS. This configuration creates an additional shock hazard on the battery circuit [10] as shown in Figure 3 [14]. In the worst case, battery voltage would add to line voltage for a combined ac/dc shock hazard. Battery workers should be aware of this hazard and wear appropriate PPE for ac line voltage if and when they enter the restricted approach boundary, even if there is no dc shock hazard across battery terminals.

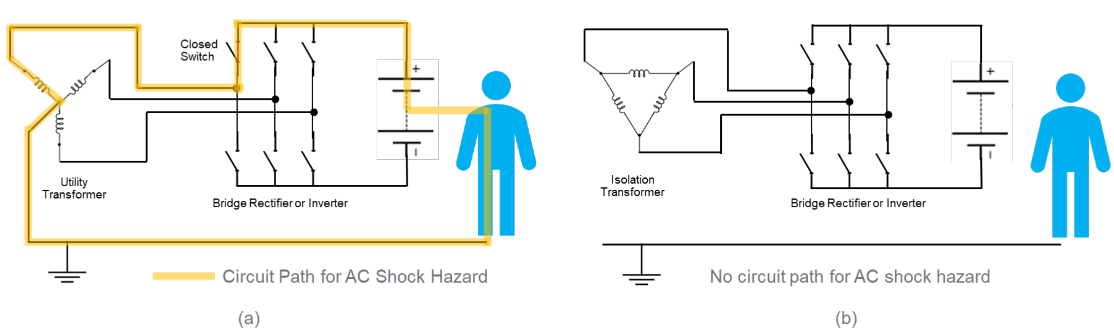


Figure 3. Non-Isolated UPS with AC Hazard on DC Bus, adapted from Annex D. in [14]

Arc Flash Hazard

While shock hazard is based on an unintended path for current through the human body, arc flash is based on a path for current through air. The ionization of air is a complex and non-linear process. An arc will tend to operate in one of two modes, though it can rapidly switch between them: high-voltage-low-current, and low-voltage-high-current. High-voltage-low-current is the kind of arc seen in a residential static discharge while the low-voltage-high-current mode is seen in arc welding. The two modes intersect at a point of minimum voltage, below which no arc can be sustained [5]. The minimum arc voltage for a given gap through air is a function only of the gap length and can be calculated empirically based on experimental results. The equation below is an approximation based on experimental data, analyzed in [5], for the minimum arc voltage as a function of gap.

$$V_{arc} = \left(20 + 0.534 z_g\right)\left(10 + 0.2 z_g\right)^{0.12}$$

where

V_{arc} is the arc voltage in the voltage
z_g is the arc gap (mm)

If we assume that the arc current is supplied by a battery, then we know that the arc voltage will drop according to the battery's discharge characteristics. We simplify these characteristics with a Thevenin source model of a battery, shown in Figure 4. Further, using the maximum power method for incident energy (IE) calculation described in Annex D of NFPA 70E [6], the magnitude of the hazard can be derived as the intersection of the battery IV curve and the arc IV curve. Any system with calculated IE below 1.2 cal/cm^2 is considered to have a low arc flash hazard.

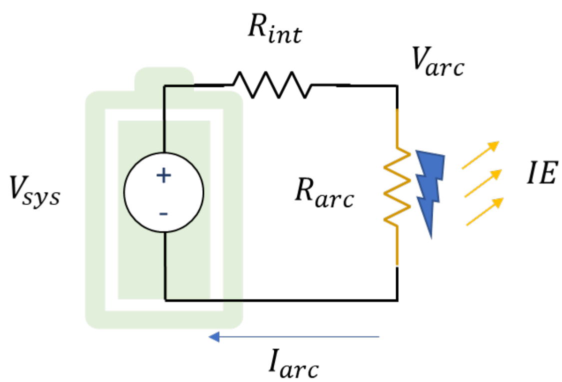


Figure 4. Simple battery arc flash model.

With these approximations in mind, two values can be calculated for a given battery: the maximum sustained arc gap, and maximum low-hazard arc gap. The maximum sustained arc gap is the gap distance, above which, any arc would quickly self-extinguish. This can occur if there is an initiating event (a small wire bridging the gap is commonly used in experiments) to supply the current required to ionize air. The wiring in a battery system has a small natural inductance that resists changes in current such that when the initiating event is cleared the circuit inductance acts as an additional voltage source to sustain the arc. However, the energy stored within the circuit inductance tends to be very small. Hence arcs initiated from a source without sufficient voltage tend to be extremely brief. This assumption would not hold in circuits with large inductances.

Figure 5 shows the calculated maximum sustainable arc gap for four battery systems used in arc flash experiments described in [7]. The four convex double-line curves represent the arcs through air for the calculated gaps, while the four-concave doted/bold lines represent the battery I-V curves. The bold portion of the battery I-V curves illustrate the region where IE would be greater than 1.2 cal/cm^2 which would incur a higher arc flash hazard for workers. The squares show the maximum power point for each battery.

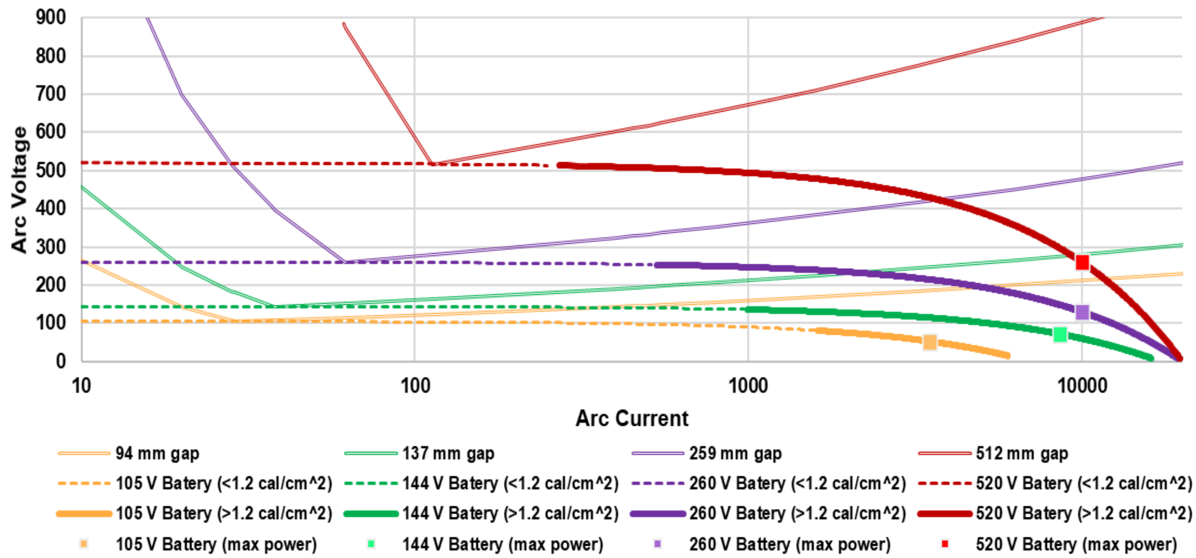


Figure 5. Maximum sustainable arc gap and battery I-V curves.

Note that an approximation of 1 mm per volt is useful for a gap above which no arc can be sustained. The maximum low-hazard arc gap is the gap distance, above which, a sustained arc would have an IE below 1.2 cal/cm^2. Figure 6 shows that the convex arc lines have lowered to intersect the bold portions of the battery I-V curves that represented high hazard. This is a much more precise estimate of the gap distance where an arc flash hazard is present in battery systems.

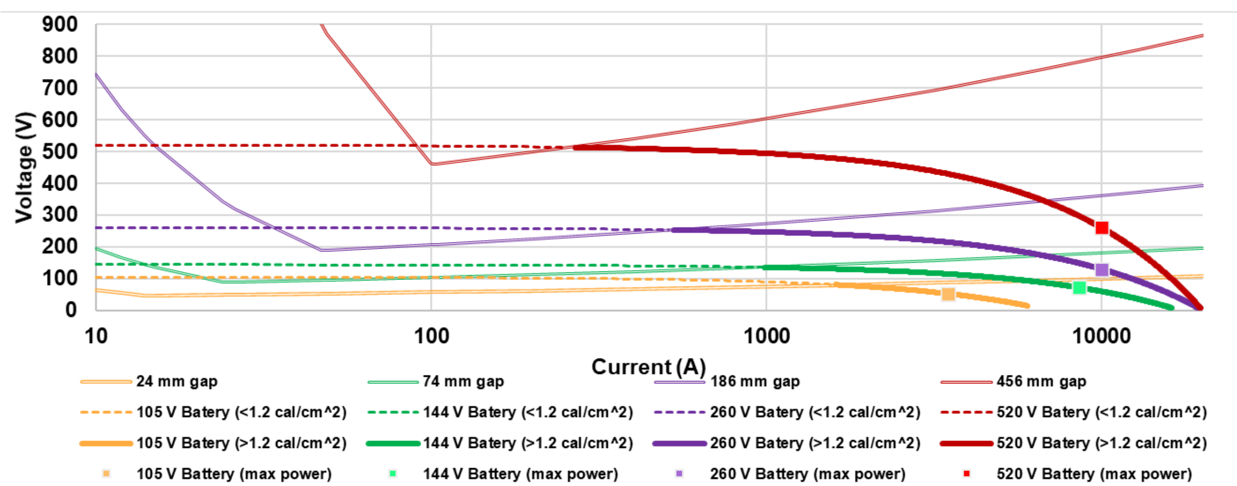


Figure 6. Maximum low-hazard arc gap and battery I-V curves.

Thermal Hazard

The thermal hazard for batteries is derived from an unintended path for current through shorting material (e.g., metallic jewelry, metallic tools, or other conductive objects) that is in contact with a worker [9]. Thermal hazard is present above a power threshold where shorting material would be likely to burn a worker before they could pull their hand away. This represents a higher likelihood, but lower consequence risk profile when compared to shock or arc flash. Higher likelihood because thermal hazard can be present even in individual battery cells but lower consequence as it is unlikely to cause death. Instead, an accident involving thermal hazard more often results in moderate to severe injury to the workers hands. This different risk profile has resulted in its omission from past worker safety standards and practices.

The magnitude of a thermal hazard can be calculated as the maximum power that can be transferred to hypothetical shorting material. Figure 7 shows a simple model commonly used to calculate the thermal hazard of a battery. This model assumes a worst-case shorting material where $R_{sh} = R_{int}$, and all power dissipated in the shorting material is converted to thermal energy.

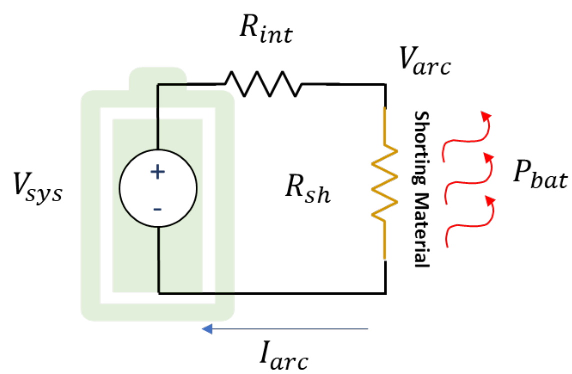


Figure 7. Simple battery thermal hazard model

The calculation for thermal hazard is then shown below.

$$P_{bat} = \frac{V_{sys}^2}{2R_{int}}$$

where

P_{bat} is the maximum power transfer to shorting material (W)
V_{sys} is the system or battery voltage (V)
R_{int} is the system or battery internal resistance (Ω)

The impact of conductor spacing on thermal hazard is to change the possible shorting material. Reducing the length of busbars and increasing the distance between battery terminals can have the net effect of reducing the likelihood and consequence of an accidental short. Further, covering bus bars with insulation can greatly reduce the likelihood of an accidental short. Lastly, NPFA 70E requires that any work performed on batteries be performed without conductive jewelry, and with tools that have insulated handles. Note that some tools with only insulated handles (as opposed to those with insulated handles and “heads,” which are much better) will have large segments of exposed metal that could cause a short. However, if the short happens in the exposed areas of the tools it will still reduce the consequence of thermal exposure to worker depending on the length and thermal conductance of the tool.

An Electrically Safer Battery Design

The requirements in the NEC are designed primarily for fire safety. Battery designers must also be concerned with electrical safety to help protect qualified workers. Qualified workers are knowledgeable about battery hazards but also perform tasks that can expose them to electrical risk. The goal for a designer should be to enable a worker to perform their tasks without exposure to shock, arc flash, or thermal hazards to a practical extent. Battery system design and installation standards should then require or recommend certain common sense design practices that allow workers to assemble, disassemble, install, and maintain batteries safely. If thoughtfully applied, these design standards can reduce costs in the long run by streamlining these activities and avoiding accidents.

Conductor Spacing Arrangement and Insulation

All electrical hazards are mitigated by increasing the separation between exposed electrical conductors. Shock and thermal burns become less likely and arc flash events become less likely and less severe. The following are recommendations for reducing the likelihood and/or consequence of electrical accidents in battery systems.

- Design the battery to separate dc voltages >100 V by distances greater than 7’ to greatly reduce the risk of shock. Avoid individual racks >100 V and switchbacks where rack-to-rack voltage >100V.
- Where full battery voltage needs to be routed in close proximity (e.g., at the inverter / charger), the design should include a method of disconnection without exposure (e.g., a mid-string disconnect switch).
- Route the most positive and negative terminals into separately enclosed panels when practical.
- Cover conductors wherever possible with string voltage rated barriers / insulation. This is in addition to the requirements of 480.10 (B) on the guarding of live parts [11]. Insulated intercell connectors are often discouraged because they can hide corrosion [10]. This can lead some to install clear plastic barriers instead which can be difficult to remove during maintenance. Hence, conductor insulation should be designed to be easily removed to perform visual inspection and voltage testing.

Disconnection and Design for Segmentation

The current NEC [11] has specific requirements for a disconnecting means, emergency disconnect, segmentation of batteries above 240 V, and signage in systems that can be remotely actuated. The following is a list of recommendations for disconnect placement and design:

- Disconnects should be located where they can be actuated without exposure to an electrical hazard (i.e., on the outside of a battery cabinet or near the door to the battery room).
- Batteries above 100 V should include mid-string disconnects sufficient to reduce the voltage of each segment to below 100 V. This would drastically reduce the risk of shock and arc flash in battery systems. The shock hazard could be all but eliminated without exposure to a hazard.
- Disconnects should be keyed, or color-coded, with the corresponding connectors such that it is difficult or impossible to connect a battery in reverse, in a loop, or across a short.

Note that many maintenance activities, such as voltage measurement, do not require a worker to cross the restricted approach boundary. Such activities should not require segmentation as it would not reduce risk.

Temporary Battery Connection

Batteries installed as a single alternate source of power in an emergency standby system according to 700.12(E) shall comply with 700.3 (F) to include permanent switching means to connect a portable or temporary battery that shall be available for the duration of maintenance or repair [11]. A battery used as an auxiliary power supply to a generator set according to 700.12(D)(3), is sized support the load for the time it takes the generator to develop power. Parrel battery strings, or groupings of parallel strings, can be counted as alternate sources of power if each are independently sized to support the load for the required duration.

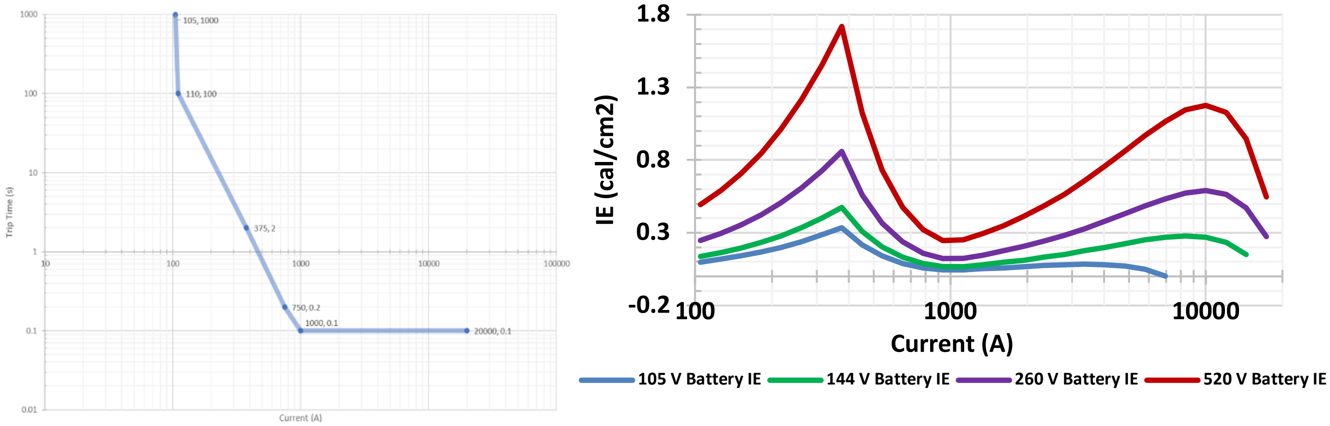
Non-emergency battery standby systems commonly serve business critical systems or processes. These systems are not required by code to have provisions for temporary substitution during maintenance or repair, as is required for emergency standby systems, because it is assumed that these systems will be disabled maintenance or repair. Because of the business criticality, temporary battery substitution is a common practice regardless of if the system is designed for it. The employer justifies the energized work required because batteries cannot be deenergized. However, batteries can be sectionalized in to lower-voltage, lower-energy segments if they are disabled first, making many necessary maintenance and repair activities electrically safer. The current state of the code has resulted in a catch 22 situation: the code does not require provisions for a temporary battery connection for non-emergency systems, yet when a temporary battery is connected, they justify the energized work to connect it as infeasible to perform deenergized. The code should be updated to make the decision about whether to disable the battery for maintenance or repairs explicit in the design. Battery systems that will be disabled for repair need no additional equipment. Battery systems that will not be disabled for repair, for whatever reason, have the option to include redundant battery strings (a common design in larger UPSs), or to have the standard equipment to enable a temporary battery connection [10].

Ungrounded Circuits (no bonding to equipment ground)

Battery circuits exceeding 100 V should operate with ungrounded conductors and should include a ground fault detector (GFD) and indicator (currently permitted by NEC article 480.13 [11]). GFDs are often included as a function within the battery charger, or a battery management system (BMS). The term ungrounded is imprecise in practice. The correct term from a safety perspective is that no-point in the battery circuit is directly bonded to the equipment ground. GFDs can also include a large resistor from the circuit to equipment ground. To protect a worker from shock hazard, current must be limited to below the dc current threshold for permanent injury [2]. The minimum resistance to ground for dc shock protection is therefore 25 Ω / V (for a maximum dc current of 40 mA). If a GFD is not installed, or not working, the resistance to ground can be checked. Using a rated multimeter, a worker can test resistance to equipment ground at the positive and negative terminals. It can be useful to have a known resistance installed somewhere nearby to test the meter on before and after a resistance to ground check. Note that a GFD is an administrative control in that it only as effective as the maintenance program that monitors it and acts if a ground fault has been detected.

Overcurrent Protection

In general, overcurrent protection is designed to prevent damage to the wires in a circuit. But breakers and fuses have long been used in ac circuits to limit arc flash hazard as well. These devices can be extremely effective at reducing the hazard in battery systems though it is much harder to get a precise estimate of battery impedance as compared to ac circuits. Battery impedance can change over time and use as well. For this reason, it can be useful to calculate the IE over a range of possible fault currents. Depending on the exact timing of the overcurrent protection device, the worst-case IE can occur under different fault currents. The figures below illustrate one such scenario. Figure 8 (a) shows a simple trip timing curve for an example electromechanical breaker. Figure 8 (b) then shows the IE, calculated using the power transfer method from Annex D of NFPA 70E [6], for each battery in described in [7] with the trip time from Figure 8 (a). NFPA 70E [6] recommends that 2 seconds is used as a maximum time which occurs for this device at a fault current of 375 A. For each of the batteries, the maximum IE occurs at this threshold 375 A because it is just low enough to avoided tripping the beaker for 2 seconds. A second peak is observed at the maximum power fault current. This analysis is consistent with the results in [8] which shows two additional examples of this effect. Because of this effect, if the disconnect breaker has field-adjustable instantaneous trip settings, it is wise to set these towards the lower end in order to limit arc flash energy, as long as they are not set so low as to possibly cause tripping during normal charging and discharging of the battery.



(a) (b)

Figure 8. (a) Simple circuit breaker trip curve, (b) Incident Energy (IE) at 45.7 cm (18in) considering circuit breaker trip curve

Example Battery Design

Consider a tiered open-air battery within a utility substation. The 120 V battery, made up of 60 – 2 V cells, must be placed in a small room to provide backup control power in case of an outage. The substation and the room are locked so only qualified personnel can enter. Figure 9 shows an example battery with several specific changes recommended to improve electrical safety. As it is, the battery has significant shock and thermal hazards for anyone performing work in the battery room. By re-arranging the batteries on the top tier, the tier-to-tier voltage that the worker is exposed to is reduced to less than 100 V. By including current rated disconnecting plugs in the longer wire runs the battery arc flash hazard in the main disconnect switch, if present, can be removed by a worker without exposure. Lastly, by covering the battery terminals with insulation, thermal injury from an accidental short circuit can be made much less likely.

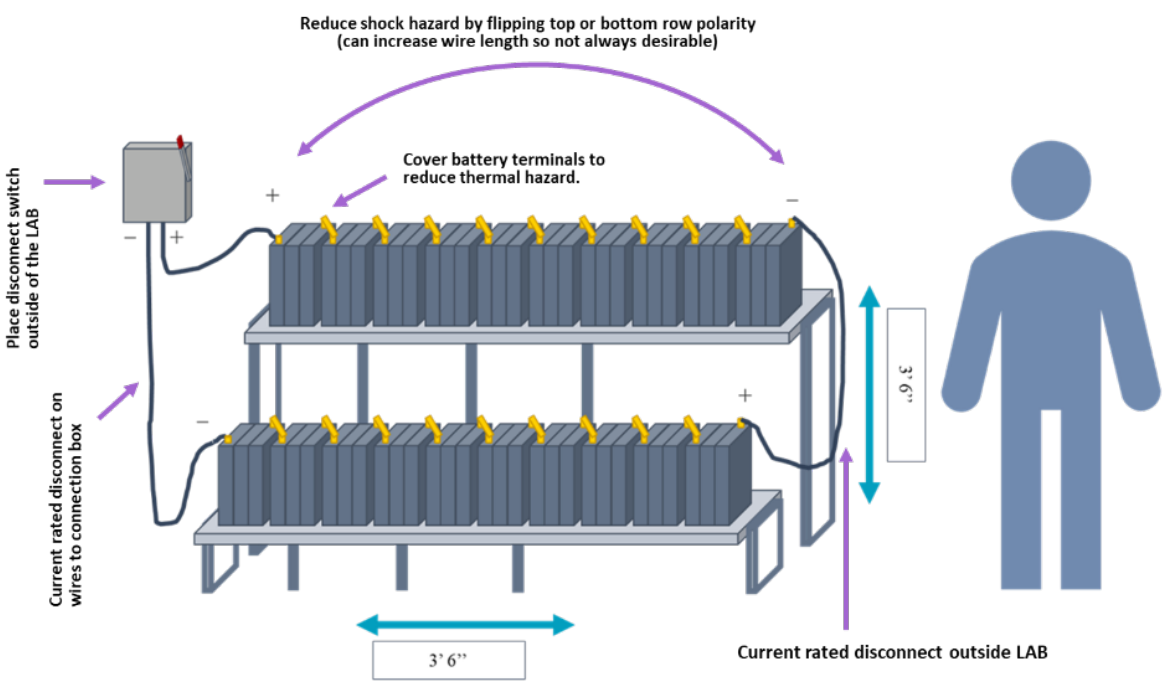


Figure 9. Example battery system with specific recommended changes

Conclusions and Draft NEC Changes

Common sense design principles can be effectively applied to reduce the risk of shock, arc flash, and thermal burns in battery systems. Shock is a result of current passing though the human body, so considering where the workers are can help configure a battery to eliminate possible scenarios where shock can occur. Arc flash is a result of current passing through open air, so increasing separation distances of exposed electrical conductors to greater than 1 mm per V can effectively prevent hazardous arcs. Thermal burn is a result of current passing through a shorting material, so considering each component of a battery system as potential shorting material can help to reduce or even eliminate thermal hazard. Many of these principles are situational as they depend on the specific battery and room. However, many are generalizable and should be applied broadly. The following is a list of most general practices identified by this paper, written in the form of specific additions and modifications to the national electrical code. These are draft comments for submission to the next revision cycle of the NEC and are subject to comment and change.

- 480.7(C) Disconnection of Series Battery Circuits: reduce voltage threshold for battery sectionalizing "Battery circuits exceeding 100 volts between conductors or to ground and subject to field servicing shall have provisions to disconnect the series-connected strings into segments not exceeding 100 volts dc nominal for maintenance by qualified persons. Non-load-break plug-in, switch, or electronic contactor disconnects shall be permitted, provided they can be locked open. Non-load-break bolted disconnects shall be permitted, provided they are installed with adequate tool clearance.

  Informational Note: Many battery maintenance activities, such as float voltage measurement, do not require a worker to cross the restricted approach boundary. Such activities should not require segmentation as it would not reduce risk."
- 480.7(F) Notification: add requirement for ac shock hazard label for non-isolated battery installations "Facilities with utility services and battery systems installed with charger or inverter connected to a grounded wye transformer shall include the following label AC HAZARD IN THE BATTERY CIRCUIT WHEN IN OPERATION and shall specify the ac phase to ground voltage."
- 480.10(B) Live parts: add guidance on battery terminal covers "Battery terminals and bus bars shall be guarded from unintended contact by insulation, insulated covers, barriers, or enclosures. Ease of removal for required maintenance should be considered."
- 480.13 Ground-Fault Detection: make current guidance a requirement "Battery circuits exceeding 100 volts between conductors or to ground shall operate with ungrounded conductors or a high resistance (greater than 25 Ohms per volt) bond to ground. A ground-fault detector and indicator shall be installed to monitor for ground faults."
- 480.14 (New clause) Temporary Battery Connection: add a requirement for battery transfer in some non-emergency standby systems "Batteries installed as a source of power in a non-emergency standby system shall comply with one of the following:
  1. The battery standby system shall be disabled for maintenance or repair. The following signage shall be durably attached within sight of the battery:

     DISABLE THE BATTERY AND CHARGER BEFORE PERFORMING ENEGIZED ELECTRICAL WORK
  2. The battery standby system shall include redundant parallel strings, or groupings of parallel strings, and permanent switching means to disabled individual strings for maintenance or repair.
  3. The battery standby system shall include shall comply with 700.3 (F) to include permanent switching means to connect a portable or temporary battery that shall be available for the duration of maintenance or repair. Parallel connection of both batteries shall be permitted."

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