EVOLVING DESIGN AND WORKER SAFETY STANDARDS FOR BATTERY ENERGY STORAGE SYSTEM

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Abstract

Technologies are rapidly evolving for Battery Energy Storage Systems (BESS), requiring new or revised design and worker safety standards. This presentation/paper will provide an overview of evolving design standards (UL, IEC, and IEEE) for the design of BESS components, and the recent and upcoming revisions for worker safety standards and safe work practices covering the thermal, shock, and arc flash hazards (NFPA and IEEE). Details of evolving worker safety standards for DC arc flash hazards will be provided, included new models for the modeling of dynamic arc behavior. The nonlinear models for various battery chemistries will be discussed.

Introduction – Energized Electrical Work on Batteries is Inadequately Covered in National Standards

In order to manage the risk of injury while performing energized electrical work on systems that can't be deenergized, both Engineering Controls (designs to protect the worker) and Administrative Controls (training, procedures, and personal protective equipment (PPE)) must be considered together. For the past 30 to 40 years, energized electrical work has been discouraged for low-voltage (<1000 V) power-delivery systems, as laid out in the 2021 Standard for Electrical Safety in the Workplace (NFPA) 70E, Article 110.3 Electrically Safe Work Condition [1], and in the Occupational Safety and Health Standards 29CRF 1910.333(a)(1), known as Subpart S [2]. Both the NFPA 70E, and the federal Subpart S state that systems "shall be deenergized before the employee works on or near them. Exceptions include critical systems (e.g., life support systems), or limitations in design or operational limitations (such as testing) or a continuous industrial process system that can't be shut down.

Such requirements to always work in an electrically safe work condition led to three characteristics of such systems and work: (a) less built-in design requirements to isolate the worker from the hazard (e.g., little to no methods to verify an Electrical Safe Work Condition without exposure to the hazards), (b) requirements for additional documentation to justify energized electrical work (e.g., the Energized Electrical Work Permit (EEWP) (NFPA 70E Article 130.2 – Energized Electrical Work Permit, and (c) more reliance on PPE for worker protection, since there is exposure during verification of an Electrically Safe Work Condition and during testing and troubleshooting.

These two key U.S. standards for low voltage electrical work, NFPA 70E and OSHA Subpart S, were clearly written for power delivery systems and not for batteries. This is consistent through the lifetime of both (70E 1979 to present) and OSHA Subpart S (1970 to present). OSHA 1910, Regulations (for the protection of workers) never mentions batteries. They do mention in 1910.333(b)(2)(ii)(D) that stored electric energy shall be released before work (such as capacitors). This is clearly not possible for batteries. NFPA 70E Chapter 3 - Safety Requirement for Special Equipment, Article 320 – Safety Requirements Related to Batteries and Battery Rooms has never stated that work on batteries is always energized electrical work, that design must focus on lessening exposure to such hazards, or that an EEWP is not required for justification of the work. 2021 NFPA Article 130.2(C) – Exceptions to Work Permit does not list battery work.

It is not the purpose of this paper to address these deficiencies in worker safety requirements for performing energized work on batteries and battery banks or the deficiency in methods of performing risk assessments for such work. This issue is being addressed at this time in proposals for changes in existing standards [3], and in the creation of new methods and standards for Risk Assessment for specialized systems [4].

The purpose of this introduction is to emphasize the differences in unavoidable energized electrical on batteries and battery banks, that current electrical worker standards do not adequately address work on batteries, and to emphasize the importance of design requirements to lower exposure to the hazards.

Relationship Between Safety Design Standards and Worker Safety Standards

Risk Assessment, as first introduced for low-voltage power-system electrical work in the 2015 NFPA 70E [1] includes consideration of (a) the consequence (e.g., level of injury) of exposure to an electrical hazard, and (b) the probability of such an exposure occurring. From the 2021 NFPA 70E Article 100 Definitions, “Risk Assessment – An overall process that identifies hazards, estimates the likelihood of occurrence of injury or damage to health, estimates the potential severity of injury or damage to health, and determines if protective measures are required.” [1]

It is important to note that the Risk Assessment process in NFPA 70E does not adequately address the importance and impact of designs to reduce the likelihood of exposure. It does state, in 2021 NFPA 70E, Article 130.4 (B) and in Article130.5(B) that the estimate of likelihood and severity shall take into account: “(1) the design of the electrical equipment, and (2) The electrical equipment operating conditions and the condition of maintenance”, but gives no guidance on how the design might lower the likelihood and severity [1].

The rapid evolution in large battery bank technologies for energy storage, backup power systems, and electric vehicles creates an immediate need to improve methods for the Risk Assessment of Battery Systems. Since such work is always energized electrical work, which increases the likelihood of injury with traditional work methods, Engineering Controls become critical, especially since there are Battery Banks for which there is no available arc flash PPE, and thus, Administrative Controls alone can’t adequately lower the risk.

Design must be taken into account when performing a risk assessment for energized work on batteries, and the consequence of exposure to the hazards must be considered when developing the design standards. Currently, many of the design standards for batteries and battery banks is occurring without adequate consideration of the protection of the workers, and current methods for risk assessment do not adequately consider the impact of design on the likelihood of exposure. The purpose of this paper is to tie these two efforts together and to improve collaboration.

History of Design and Worker Safety Standards Relevant to Batteries/Battery Banks

Design standards for lead-acid (flooded and Valve-Regulated) have existed for decades, as this was the primary rechargeable battery technology for Standby Systems (Uninterruptible Power Supplies [UPS] and stationary standby dc plants). Lithium-based, sodium-beta, and flow batteries are newer technologies and date back 10 to 20 years. The author is not an expert in the history of these standards.

Worker safety standards for non-60 Hz power began to evolve merely 14 years ago in NFPA 70E in the U.S.

OSHA Subpart, sections 1910.301 through 1910.308 was based on the existing design standards for facility power (i.e., the National Electrical Safety Code). Sections 1910.331 through 1910.335 for worker safety was based on the needs of workers for the systems described in the design sections, i.e., facility power workers. DC power and batteries were never mentioned. The focus was on ac power, as evidenced by the use of terms such as three phase power, rms values, etc.

NFPA 70E was first created in 1979 and was solely about facility worker safety for ac 60 Hz power. In the 2000 edition a new chapter was created for Special Equipment and included Articles on Batteries and Electrolytic Cells. At this time, the thermal and arc flash hazards were not recognized in the standard. A new article on the hazards with R&D equipment was added in 2009 (Article 350). DC shock and arc flash hazards were added in the 2012 edition. In the 2021 edition a new article 360 and a new Annex R were added on Capacitor Safety. The 2024 edition will update all articles in Chapter 3 – Special Equipment, with consistent thresholds for DC thermal, shock and arc flash thresholds, and capacitor hazard thresholds. The 2024 edition will introduce the threshold for the thermal hazard, for the first time. Figure 1 summarizes the evolution of NFPA 70E focused on Special Equipment and non-60 Hz electrical hazards [5].

Figure 1. Summary of the Evolution of NFPA 70E – Standard for Electrical Safety in the Workplace

year	# pages Design	# pages Safe Work	#pages Maintenance	# pages Special Equipment	#pages Annexes	New material
1979	47				19	Appendix A – definitions
1981	45	15			19	
1983	45	15	10		19	
1988	17	5	3		8	Format change
					# An	
1995	19	11	2		7	Definitions moved to front of Standard, Added 5 Appendices
2000	35	19	3	8	8	
2004	40	16	5	12	13	Added 5 Annexes
2009	0	16	4	12	15	**350 – R&D.**
2012	0	30	4	9	16	**dc shock 100 V, dc arc flash**
2015	0	29	4	9	16	Risk assessment
2018	0	27	4	8	17	**50 V/100 V dc**
2021	0	27	4	10	18	**360 and Annex R capacitors**
2024	0					**will add thermal hazard, update RF hazards, clean up Ch. 3**

Electrical Hazards for Batteries and Battery Banks and Current Safety Standards

Three primary electrical hazards are covered in the 2021 NFPA 70E, thermal, shock and arc flash. In addition, a fourth hazard, the acoustic hazard, was added for capacitors in Article 360. The acoustic hazard is not yet clearly addressed for ac power and dc systems other than capacitors. There are plans to better address acoustic hazard thresholds in the 2027 NFPA 70E.

Thermal Hazards

The thermal hazard exists when high currents pass through metal objects in contact with a worker causing external burns to the skin. They can cause significant injury, but there are no known fatalities. The metal carrying the current might be a watch band, rings, bracelets, or necklaces, uninsulated tools, or other metal objects in contact with the skin that might accidently bridge two terminals. There are cases of lost fingers and hands. A single 12-V car battery has no shock or arc flash hazard, but a significant thermal hazard, with a typical short circuit current of up to several thousand amps, pushing up to 40 kW through the metal object. Car batteries are often treated rather casually since there is not a shock hazard, but most of the debilitating injuries to hands and fingers have occurred to automobile technicians and home owners on a single car battery.

Even up to the 2021 NFPA 70E, the thermal hazard was poorly addressed, primarily since ac control circuits below 50 V ac do not have sufficient short circuit current to cause injury. Thus, NFPA 70E did not address the thermal hazard of batteries. Article 110.4 Energized Work, section (C) Equipment Operating at Less Than 50 V, states that such equipment does not need to be put into an Electrically Safe Work Condition, when “there will be no increased exposure to electrical burns or to explosion due to electric arcs.” This is rather unclear, as “exposure to electrical burns” is not explained, and “explosion due to electric arcs” is inaccurate. Low voltage arcs, such as a welder running at 15 V and 300 A does not have an explosion, but the arc current is certainly a hazard to a worker’s bare hands. Essentially, NFPA 70E did not require a risk assessment for a 48 V, 200 kA battery bank, which has a significant thermal hazard.

The thermal hazard was first quantified at the 2009 IEEE IAS Electrical Safety Workshop [6], in the 2013 DOE Electrical Safety Handbook [7], and in an IEEE IAS publication [8].

The thermal hazard and thresholds will be in the 2024 NFPA 70E, which has already passed the final vote, and will be published in September 2023.

The thermal hazard threshold is at > 1,000 W for < 100 V dc. Above 100 V dc the shock hazard exists, and above 150 V dc the arc flash hazard must be analyzed (note that the 150 VDC arc flash values is what will be in the 2024 NFPA 70E, and is higher than what was in the 2021 version of NFPA 70E due to additional research, which is described in the following sections). The engineering and administrative controls to prevent injury from shock and arc flash will also prevent injury from the thermal hazard.

DC Shock Hazards

The dc shock hazard was never mentioned in OSHA subpart S and was not in NFPA 70E until the 2012 edition [1]. Until the 2012 edition, NFPA 70E contained one table of Approach Boundaries for Shock Protection. Although a waveform was not mentioned, the voltage ranges in the table were phase-to-phase and rms values. The intent was clearly ac. The threshold for ac shock was set at 50 V rms ac.

The shock hazard for all waveforms was first quantified at the 2009 IEEE IAS Electrical Safety Workshop [6], in the 2013 DOE Electrical Safety Handbook [7], and in an IEEE IAS publication [8]. These thresholds were clarified, updated, and harmonized with IEC standards [9, 10] and with IEEE Std C95.1 [11], and presented in the IEEE IAS 2022 Electrical Safety Workshop, “Electric Shock Hazards Beyond 50/60 Hz and DC” [12]. The current shock thresholds for dc throughout all of Chapter 3 – Special Equipment in the 2024 NFPA 70E will at > 100 V dc and > 40 mA dc. This includes all batteries and battery banks.

DC Arc Flash Hazards

AC arc flash hazards were first quantified and brought to the electrical standards efforts by the pioneering efforts of Ralph Lee in 1982 [13]. They were then incorporated into the 2004 NFPA 70E requiring an arc flash hazard analysis (since the 2015 edition known as a risk assessment) [1], and guidance was provided by IEEE 1584 [14] and Annex D of the 2004 NFPA 70E. IEEE 1584 was updated in 2018 [15].

DC arc flash was first introduced in the 2012 NFPA 70E simultaneously with the introduction of the dc shock hazard. Annex D was updated to include a section on guidance for dc arc flash incident energy analysis. The three methods reviewed all assumed a static arc that continued without change until interrupted by overcurrent protection. The three methods are known as the Maximum Power Transfer method [16,17], the Kinectrics empirical model based on laboratory tests [18], and the Ammerman circuit model [19]. At this point (2012) there was only one publication on testing for dc arc flash incident energy [18]. In NFPA Article 130 from the 2012 to the 2021 edition, the requirements imply that an arc flash risk assessment must be performed for any DC voltage above 100 V dc. However, 6 new testing studies had been done between the 2012 and the 2021 editions [5], so the 100 V dc arc risk assessment will be changed to 150 V dc in the 2024 NFPA.

A comprehensive review of arc flash for all waveforms began in 2015 in a presentation at the IEEE IAS ESW [20] and with the IAS journal publication in 2017 [21]. New models were proposed at the 2023 IEEE IAS that includes consideration of the dynamic behavior of dc arcs [5]. The development of these new arcs was largely stimulated by the need to better analyze the dc arcs from large battery banks. Studies are continuing for dc arc flash analysis and this will likely result in important changes to Annex D in the 2027 NFPA 70E and to current static models being used by dc arc flash analysis providers. This is a rapidly changing area.

DC Electric Shock and Arc Flash Fatalities

There were a number of myths and anecdotal stories about the hazards of dc shock and arc flash that were addressed by a comprehensive study of all known fatalities in the 34-year OSHA fatality database [22]. In the interest of space this study will not be described here, but the findings were significant. DC hazards had been made bigger than life.

Electrical Worker Safety Standards – the Future

The following is an evolving list of Worker Safety and Design Standards relevant to Batteries and Battery Banks. Electrical vehicles are not covered here.

The author has 23 years of participation in U.S. electrical worker safety standards, and has a good understanding of their scope, content, and history. The author is a key contributor to development of these standards, especially all dc applications, including batteries, capacitors, and supercapacitors.

NFPA 70E

The upcoming publication of the 2024 NFPA 70E (September 2023) will include the following approved changes:

(1) Moving the threshold for requiring a dc arc flash risk assessment from 100 V dc to 150 V dc,
(2) Updates of the thresholds for rf shock hazards to IEEE Std. C95.1-2019, and
(3) Alignment of dc, capacitor, and rf thermal and shock thresholds throughout Chapter 3 – Special Equipment, including Articles 310 Safety-Related Work Practices for Electrolytic Cells, 320 – Safety Requirements Related to Batteries and Battery Rooms, 330 – Safety-Related Work Practices: Lasers, 340 – Safety-Related Work Requirements: Power Electronic Equipment, 350 – Safety-Related Work Requirements: Research and Development Laboratories, and 360 – Safety-Related Work Requirements for Capacitors.

Public inputs (proposed changes) for the 2027 may include any or all of the following:

(1) Article 320 - Battery bank safe work practices – procedures to perform risk assessment and develop low risk procedures for performing energized electrical work on battery banks [3],
(2) Expanding Article 320 to include all battery chemistries. Currently Article 320 focuses on lead-acid banks,
(3) Reorganizing Chapter 3 for better flow, defining the unique hazards in special equipment, followed by examples,
(4) Rewriting Annex D.5 – Direct-Current Incident Energy Calculations to take into account multiple new testing data and proposed new dynamic models,
(5) Addressing the acoustic hazard with proposed models and thresholds to cover facility power, battery banks, supercapacitors and capacitors, and
(6) Other public inputs are welcome.

IEEE

Currently the only IEEE standard for electrical worker safety is IEEE/ANSI Standard C2 – 2023, National Electrical Safety Code, for utility (transmission and distribution) work [23].

Under development is a proposed Standard for Risk Assessment for Working on Special Electrical Equipment. This proposed standard would complement Chapter 3 of NFPA 70E by addressing risk assessment methods for special equipment such as battery energy storage banks, solar power, electric vehicles, dc transmission and distribution, large scale (MW) power conversion between dc and ac (invertors and rectifiers), capacitor banks, and supercapacitors.

At the 2023 IEEE IAS Electrical Safety Workshop held in Reno, Nevada on March 13 – 17, 2023 there was an expanding participation from both the battery energy storage and electric vehicle communities. Discussions resulted in proposals to create two new working groups for these two evolving technologies. This could result in new IEEE standards for working on these energized systems.

Global

This paper does not cover international design standards for batteries and battery banks (i.e., IEC standards). However, it is worth discussing the current state of, and proposed international worker safety standards [24].

There are many electrical worker safety standards, found in the larger countries, including:

U.S. – NFPA 70 E
Canada – Z462
Mexico – NOM 029
Brazil – NR10
Europe - IEC 60364-4
Europe – EN 50110-1
Germany – VDE 0100 series
France – NF C 15-100
Russia – OKC 13.260
China – Order No. 70
Australia – AS 3000
and more

A comparative review of NFPA 70E, Z462, and EN 50110 was presented at the 2023 IEEE IAS ESW [25]. Two important conclusions were: (a) the three standards are not consistent, especially contrasting the two North American standards (NFPA 70E and Z462) with the European standard (EN 50110), and (b) work on electric vehicles is not covered in any of the worker standards.

As a result of these gaps, IEC has accepted the formation of a project committee for writing a global electrical work safety standard [25].

Electrical Design Standards for Batteries and Battery Banks – Current and Evolving

In contrast to the above worker safety standards, the author is a new participant in battery design standards and working groups. This new participation is for the purpose of (a) contributing the need for worker protection considerations into the design standards, and (b) better understanding the design standards in order to create new IEEE Risk Assessment standards for special equipment, including stationary and mobile battery banks. The below list of design standards is not complete, but is what the author has gathered to date. Some of these standards are new, and still in draft form.

IEEE Battery Standards and Working Groups

Battery Technologies

IEEE WG 1679.1: IEEE Guide for the Characterization and Evaluation of Lithium-Based Batteries in Stationary Applications
IEEE WG 1679.2: IEEE Guide for the Characterization and Evaluation of Sodium-Beta Batteries in Stationary Applications
IEEE WG 1679.3: Draft Guide for the Characterization and Evaluation of Flow Batteries in Stationary Applications
IEEE WG 1679.4: Draft Guide for the characterization and evaluation of alkaline batteries in stationary applications

Valve Regulated Lead Acid (VLRA)

IEEE Std 1187-2013: IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Batteries for Stationary Applications
IEEE Std 1188 – 2005: IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead- Acid (VRLA) Batteries for Stationary Applications (New revision now in ballot and has more info, similar to 1187)
IEEE Std 1189 -2007: IEEE Guide for Selection of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications
IEEE Std 1361 -2014: IEEE Guide for Selecting, Charging, Testing, and Evaluating Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems
IEEE Std 1561 -2019: IEEE Guide for Optimizing the Performance and Life of Lead Acid Batteries in Remote Hybrid Power Systems
IEEE WG 1562/937: Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems
IEEE WG 1562/1013: Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems
IEEE WG 1562/937: Guide for Test and Evaluation of Lead-Acid Batteries Used in Photovoltaic (PV) Hybrid Power Systems
IEEE WG 450: Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications
IEEE Std 1661™-2019: IEEE Guide for Test and Evaluation of Lead-Acid Batteries Used in Photovoltaic (PV) Hybrid Power Systems
IEEE Std 450-2020: IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications

IEEE Std 484-2019: IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications
IEEE Std 485-2019: IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications

Lithium Ion

P2962™/D32: Draft Recommended Practice for Installation, Operation, Maintenance, Testing, and Replacement of Lithium-ion Batteries for Stationary Applications
IEEE WG 3163: Recommended Practice for Sizing Lithium Batteries for Stationary Applications

Nickel Cadmium

IEEE Std 1106-2015: IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications
IEEE Std 1115 -2014: IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications

Uninterruptible Power Supplies (UPS)

IEEE Std 1184-2022: IEEE Guide for Batteries for Uninterruptible Power Supply Systems

Battery Energy Storage and Stationary Batteries

IEEE Std 1491 - 2012: IEEE Guide for Selection and Use of Battery Monitoring Equipment in Stationary Applications
IEEE Std 1547.4 - 2011: IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
IEEE Std 1657 - 2018: IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries
IEEE Std 1679 - 2020: IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications
IEEE Std 3001.2 - 2017: IEEE Recommended Practice for Evaluating the Electrical Service Requirements of Industrial and Commercial Power Systems
IEEE Std 946 - 2020: Recommended practices for the design of dc power systems for stationary applications
IEEE WG 2993: Recommended Practices for Energy Storage System Design using Second-life Electric Vehicle Batteries
IEEE WG 1375: Guide for the Protection of Stationary Battery Systems
IEEE WG 2686: Recommended Practice for Battery Management Systems in Energy Storage Applications
IEEE WG 2688: Recommended Practice for Energy Storage Management Systems in Energy Storage Applications

Underwriters Laboratory (UL)

UL 1973- Batteries for Use in Light Rail (LER) and Stationary Applications
UL 2056 – Outline of Investigation for Safety of Lithium-Ion Power Banks
UL 9540 – Energy Storage Systems and Equipment
UL 9540A - ANSI/CAN/UL Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems

NFPA

NFPA 855 - the Standard for the Installation of Stationary Energy Storage Systems, 2019

IEC
IEC 61960-3 – Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes – Secondary Lithium Cells and Batteries for Portable Applications – Part 3: Prismatic and Cylindrical Lithium Secondary Cells and Batteries Made from Them
IEC 62485-2 – Safety Requirements for Secondary Batteries and Battery Installations: Stationary Batteries
IEC 62619 – Secondary Cells and Batteries Containing Alkaline and Other Non-Acid Electrolytes – Safety Requirements for Secondary Lithium Cells and Batteries, for Use in Industrial Applications
IEC 62933-5-2 – Electrical Energy Storage (EES) Systems – Part 5-2: Safety Requirements for Grid-Integrated EES Systems – Electrochemical-Based Systems

Summary

In developing new risk assessment methods for working on energized battery banks it is important to coordinate the rapidly evolving design standards with the rapidly evolving worker safety standards. Several new proposals for improvement in worker safety standards were listed. The purpose of this paper is to further stimulate communication and coordination between these two efforts, design and safe work practices.

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The author would like to recognize the enthusiasm and desire for collaboration between the IEEE Power and Energy Society (PES), which is mostly focused on design, and the IEEE Industry Application Society (IAS), which is mostly focused on safe work practices. This collaboration will result in ever improving design and worker safety standards for batteries and battery banks.

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