REPLACING LEAD-ACID AND NICKEL-CADMIUM STATIONARY BATTERIES WITH LITHIUM-ION – IT'S NOT A SIMPLE SWAP

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Abstract – The rapid advancement and adoption of lithium-ion batteries in battery electric vehicles and battery energy storage systems has people considering replacing their existing lead-acid and nickel-cadmium stationary batteries with lithium-ion. The potential space and weight savings can be substantial however safety, reliability, and cost are major considerations. Lithium-ion batteries pose fire risks and increased building fire loads that lead-acid and nickel-cadmium batteries do not present. Additionally, lithium-ion batteries have reliability issues, not present in lead-acid and nickel-cadmium batteries, which must be addressed. Inserting lithium-ion batteries into traditional lead-acid and nickel-cadmium roles is not a simple battery swap. The additional costs and risks must be carefully evaluated when considering a swap from traditional technologies to lithium-ion batteries.

Index Terms — Stationary/Standby Battery Systems, Lithium-ion Battery (LIB), Battery Energy Storage System (BESS), Energy Storage System (ESS), Thermal Runaway, Vented Lead Acid (VLA), Valve Regulated Lead Acid (VRLA), Nickel-cadmium, (NiCd).

I. INTRODUCTION

Lead-acid (LA) and nickel cadmium (NiCd) battery systems provide control and reserve power for modern life as we know it. These systems provide breaker tripping, closing and control power for switchgear, power for automated controls, power for field flashing of generators, power for emergency lube oil and seal oil pumps and other critical motors, reserve power for uninterruptible power systems (UPS) systems, control power for many petrochemical processes, and operating power for critical communication systems. In short, these battery systems make modern life possible, and they surround us.

A LA or NiCd stationary/standby 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, because the cost of a stationary battery failing to support its connected load under worst case conditions can easily reach into the millions of dollars.

A typical stationary/standby DC system consists of a battery, rectifier/charger, and load connected in parallel. In this arrangement the battery is maintained at a constant voltage, (float voltage), and only discharges during an input power failure to the rectifier/charger, a failure of the rectifier/charger, or when the load exceeds the capability of the rectifier/charger such as when tripping or closing circuit breakers in switchgear.

The battery is held at or very near 100% State-Of-Charge (SOC) in an on-line standby mode waiting for an unplanned discharge. See figure 1. Depending upon system design, there may or may not be an overcurrent protection device between the battery and DC bus, but there are normally no contactors or semiconductors between the battery and the load.

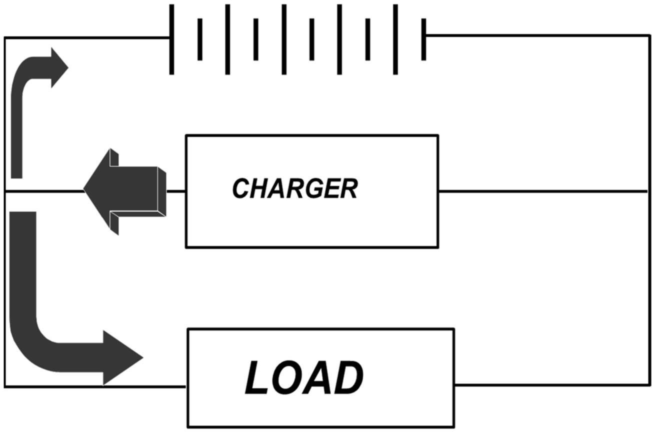

Figure 1. Simplified DC System

Due to the straightforward design of stationary/standby DC systems it appears to be a simple swap to replace the conventional LA or NiCd battery normally used in these systems with a voltage and capacity comparable lithium-ion battery (LIB). However, it is not a simple swap. Two significant issues must be overcome with LIB's, safety, and reliability. LIBs present a fire and flammable/explosive/toxic gas hazard due to thermal runaway. Additionally, there is a reduction in reliability resulting from the various devices required to make a LIB operational.

For comparative purposes, this paper will limit the discussion to a battery system of 125 Vdc and approximately 200 Amp-Hours (Ah) capacity as this is a very common battery size in the petrochemical industry.

II. THERMAL RUNAWAY HAZARD

LA and NiCd batteries do not present a thermal runaway hazard as they do not have enough energy to enter a thermal runaway condition without an external energy source (battery charger).

At the June 2023 meeting of the IEEE Energy Storage & Stationary Battery (ESSB) committee, a new term, "Thermal Walkaway," was approved to differentiate the thermal hazard of LA and NiCd batteries from LIBs. Thermal walkaway is a slow heating process driven by an external current source (charger) and caused by abuse, neglect or internal cell failures that results in overheating and increased gas production in a LA, NiCd, or other aqueous chemistry battery which can be controlled by removal of the charging source or reduction of the charging current.

Thermal walkaway and thermal runaway are vastly different thermal events. Thermal walkaway is a slow process that can be easily prevented by use of a temperature compensating charger with a remote temperature probe placed on the battery. It can also be easily detected by either automatic monitoring or maintenance personnel and once detected it can be easily arrested or stopped by reducing charging current or removing the charging source.

Conversely, thermal runaway can occur very rapidly and once started cannot be stopped. Thermal runaway is defined as self-heating of an electrochemical system in an uncontrollable fashion by National Fire Prevention Association (NFPA) standard 855-2023. [1] Self-heating cannot be stopped once the internal temperature exceeds the threshold temperature for that chemistry and cell design. The resulting reactions produce significant heat and copious quantities of toxic, flammable, and potentially explosive gases, and do so very quickly. The threshold temperature for thermal runaway in LIBs is typically between 100° and 300°C, dependent upon chemistry, cell design, and research paper cited. [1] [2] Thermal runaway can be initiated by an external heat source, internal cell fault or short circuit, overcharging, external short circuit, or physical damage. The overarching safety issues with LIB's are fire and copious quantities of flammable/explosive/toxic gases resulting from thermal runaway.

All commercially available LIB's can go into thermal runaway. *Note: Research and development of LIB's is in constant progress throughout the world. At the time of this writing, the author is not aware of any commercially available LIB's suitable for stationary battery service that cannot be driven into thermal runaway.*

Because thermal runaway is a real possibility the LIB must be designed to limit or prevent propagation of thermal runaway from one cell to another. Additionally, the facility or container the battery is in must be designed to contain any resulting fire and manage the off gases in a manner that prevents deflagration or explosion. These requirements are listed in NFPA 855 [1], NFPA 68 [2], NFPA 69 [3], and the International Fire Code, (IFC) [4]. The 2024 edition of the IFC essentially endorses the requirements and exceptions listed in NFPA 855.

III. LIB Installation Requirements

LIB's ≥ 20 kWh require the following according to 2023 edition of NFPA 855 and the 2024 edition of the IFC:

1. UL9540 listing. [3]
2. Large-scale fire test conducted on a representative LIB system in accordance with UL9540A. [4] The testing shall be conducted or witnessed and reported by an approved testing laboratory and show that a fire involving one Energy Storage System (ESS) will not propagate to an adjacent ESS, and where installed within buildings, enclosed areas and walk-in units will be contained within the room, enclosed area or walk-in unit and not present a deflagration or explosion hazard for the duration of the test. The test report shall be provided to the Authority Having Jurisdiction (AHJ) for review and approval. [5] [6] [7] & [8]
3. Supplemental report prepared by a registered design professional with expertise in fire protection engineering that provides interpretation of the test data in relation to the installation requirements for the battery system. [5] [6] [7] & [8]
4. Automatic fire suppression and explosion/deflagration protection as determined by the supplemental report, (c. above). [5] & [8]
5. Detailed construction documents which must be submitted to the AHJ for approval. [5] & [8]
6. Detailed commission plan including commissioning testing, commissioning report, and corrective action plan. [5] & [8]
7. Acceptance testing showing that the LIB system operates in accordance with the manufacturer's instructions. [5] & [8]
8. Commissioning report describing the results of the system commissioning, including the results of the initial acceptance testing. This information shall be provided to the AHJ prior to final inspection and approval and maintained at an approved on-site location. [5] & [6]
9. Emergency operations plan and local staff training. [5] & [8]
10. Decommissioning plan to include plans to remove a damaged LIB from service. [5] & [8]
11. Minimum 2-hour fire rated barriers if the LIB is in the same structure as administrative or support personnel. [5] & [8]

Additionally, storage of LIB's poses safety issues like fully installed LIB's. See "Storing Lithium Batteries – The Safety Needs and Regulatory Requirements" by C. Ashton and M. O'Brien presented at Battcon 2023 for more information. [9]

Except for "11" above, none of these requirements apply to LA or NiCd batteries until the battery capacity ≥70 kWH or the quantity of electrolyte exceeds 50 gallons and even then, there are exemptions for certain applications. [5] & [8]

IV. Safe LIB Chemistries, Are They Really Safe?

Lithium iron phosphate (LFP) batteries and lithium titanate (LTO) batteries are the two LIB chemistries typically regarded as the safest and thus the most likely to be considered for stationary/standby use. The primary reason these chemistries are touted for their safety is their lower energy density. Lower energy density typically equates to lower thermal runaway risk and severity. While these chemistries are safer than other more energy dense chemistries this does not alter the NFPA 855 or IFC installation requirements.

LFP batteries have been advertised as "safe" lithium-ion batteries. Some manufacturers claim that their LFP battery is a direct replacement for Valve Regulated Lead-Acid (VRLA) and has no thermal runaway risk. Scientific papers such as Investigating Thermal Runaway Triggering Mechanism of The Prismatic Lithium Iron Phosphate Battery Under Thermal Abuse by Zhijuan Zhou published in ScienceDirect Renewable Energy Volume 220, January 2024, [1], show that LFP batteries can enter thermal runaway and thus thermal runaway is still a risk for LFP batteries.

LTO batteries have the lowest energy density of any commercially available LIB and thus have a lower risk of thermal runaway, but thermal runaway is still possible. See "The Combustion Behavior of Large-Scale Lithium Titanate Battery" by Huang, P., Wang published at Scientific Reports, January 2015. [2]

LIB cells sizes are still relatively small compared to commercially available lead-acid and NiCd cells. This means that even for a relatively small battery (200Ah), the LIB chemistry chosen will likely use two to four parallel cells to achieve the Ah requirement. Groups of identical parallel cells are then connected in series to reach the desired DC system voltage. This results in more total cells than a comparable lead-acid battery. The higher the cell counts the higher the risk for thermal runaway.

The results from a large-scale fire test (9540A test) conducted on a representative LFP or LTO system could be used to convince the AHJ that some LIB installations requirements can be safely altered.

V. LIB System Reliability

LIBs require a Battery Management System (BMS) for safe operation. The BMS must, at a minimum, prevent cell overcharge, cell over discharge, cell and battery overtemperature, and cell and battery under temperature operation, and protect the battery from damage due to an external short circuit.

The BMS must also perform active cell SOC balancing. This is required at the cell level since LIB cells cannot be overcharged without damage and potential thermal runaway. Conventional LA and NiCd batteries do not require active cell SOC balancing as this can be achieved by equalize charging the entire battery. The energy from any overcharge is consumed by the water via electrolysis.

Protecting the LIB requires computer controlled disconnect devices to isolate a string of cells, or the entire battery, and semiconductor switches for cell balancing. These disconnect devices will likely be a combination of semi-conductors, contactors, and fuses or circuit breakers. The presence of contactors or semiconductors in the power path reduces the reliability of the battery system. These devices are not present in stationary/standby lead-acid and NiCd systems.

Additionally, the decision-making process of keeping the LIB in a safe operating state typically requires a microprocessor or microcomputer. The LIB will become inoperable or unsafe should either the controller or isolation/interrupting device(s) fail. These devices are not present in stationary/standby lead-acid and NiCd systems.

The very devices needed to make LIBs safe also reduce the reliability of the battery system. Adding parallel battery strings can increase the system reliability, but how many redundant batteries are necessary? This question has prompted much discussion in the various IEEE ESSB working groups. The general consensus is that at least one redundant battery is needed, (N+1 redundancy), but is that sufficient? That question has yet to be answered. For the purposes of this paper one redundant battery string is enough. This means that an additional parallel string in excess of the number of strings used to reach the comparison capacity (200Ah) is required for LIBs.

VI. Battery Chargers/Rectifiers

The battery charger/rectifier commonly used with LA or NiCd batteries may not work well with LIBs. LIBs cannot be overcharged, and their internal losses are significantly less than LA or NiCd batteries. This can make float charging very problematic.

Some chargers are designed to always operate in parallel with a LA or NiCd battery and have poor regulation qualities and/or high output ripple voltage without a battery connected. The battery provides output filtering of the charger and supplies transient or short duration loads. Such chargers are incompatible with LIBs.

Ideally, the BMS should be able to control the charger/rectifier and the charger should be well filtered and very responsive to load changes. Many newer microprocessor-controlled chargers can interface with a BMS. It is essential that the charger/rectifier be thoroughly evaluated to ensure compatibility with the selected LIB.

VII. Maintenance & Testing

LIBs are not maintenance free. IEEE P2962 Draft Recommended Practice for Installation, Operation, Maintenance, Testing, and Replacement of Lithium-ion Batteries for Stationary Applications [10] is currently under development and nearing maturity. LIB maintenance moves from the cell level needed in lead-acid and NiCd batteries to more system and controls maintenance (BMS maintenance).

Capacity and/or functional discharge testing is required and may be more important for LIBs than with lead-acid and NiCd batteries as the BMS may become uncoordinated with the actual condition of the LIB due to the very infrequent discharges experienced with stationary batteries. In stationary/standby service the battery rarely discharges. Infrequent discharges reduce the LIB BMS's ability to accurately determine State of Health (SOH) and SOC, thus increasing the importance of capacity or functional discharge testing.

VIII. Sizing LIBs for Stationary/Standby Applications

Presently, there are no industry standards for sizing LIBs for stationary applications. Sizing batteries for simple load profiles used with UPS or telecom applications is fairly straight forward. However, sizing batteries for complex load profile such as those met in switchgear and power plant operation is not. IEEE P3163 Draft Recommended Practice for Sizing Lithium Batteries for Stationary Applications [11] is in early development.

LIB manufacturers normally have proprietary software for their products that are used for sizing LIBs. In the absence of industry standard guidance, the user must rely on the chosen LIB manufacturer to size the battery for their application without independent verification.

LA and NiCd batteries each have specific industry standards for sizing:

1. IEEE 485 IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications [12]

2. IEEE 1115 Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications [13]

IX. Cost and Physical Size Factors

This paper began with the premise of replacing an existing 125 Vdc 200 Ah lead-acid battery with a comparable LIB. As previously discussed in section V. LIB System Reliability, the LIB must have an additional parallel battery for reliability (N+1 redundancy).

Figure 2 shows the cost and size factors for a 125 Vdc 200 Ah vented lead-acid (VLA), valve regulated lead-acid (VRLA), NiCd and LIBs. See appendix A for more detailed information.

Considerations were made for establishing a direct comparison between the selected chemistries based on industry/manufacturer standard installation practices. Cost and dimensions for VLA and NiCd systems as shown in Figure 2 include spill containment for liquid electrolyte hazard, while the VRLA system does not have spill containment due to its classification as “non-spillable”.

Similarly, the LIB chemistries included are considered based on their respective manufacturer standard installation practices; each employing their own proprietary racking, cabinets, monitoring, and interface. For comparison’s sake, it can be noted that liquid electrolyte spill containment is not a typical consideration for LIBs.

The size factors in Figure 2 are based on a typical installation of each chemistry, though other configurations exist. For example, one of the advantages of VRLA technology when compared to VLA or NiCd is the ability to mount cells horizontally in compact modules. This allows for system volume and particularly footprint to be minimized as demonstrated by the sub-unity factors shown in Figure 2.

One of the most widely touted benefits of LIB technology over its LA counterpart is energy density in terms of volume and weight. The comparison demonstrates the reality of the space saving ability of LIB systems at the scale considered after accounting for all battery and tie cabinets needed to reach the comparison capacity. In terms of volume, the Super LFP (SLFP) system considered shows improvement over VLA, though the LTO system exceeds the base VLA system, defying the expectation.

Footprint is a common limitation in substation switchgear building design making this comparison potentially more influential to typical industry decision making. Again, in this comparison the SLFP system shows improvement over vented lead acid, and in this case the LTO system also shows improvement, however minimal. The savings of footprint space are in line with the expected benefits of switching to LIB from VLA or NiCd, however, neither of the LIB systems considered compares well to VRLA on volume or footprint, showing that energy density of LIBs at this scale is less benefit over older technologies than perceived.

Analysis of the weight factors of each system shows the expected reduction in weight for LIBs over lead-acid chemistries. Again, in this comparison the delta between LIB and lead-acid is minimized by the need for additional components and cabinetry, showing that the difference in energy density by weight is less dramatic than perceived.

System costs compared here are based on typical sale to customer prices using even margins across the board and typical distributor costs for each system. In this case distributor costs include a similar discount off list across all equipment manufacturers compared. Cost factor is the widest deviation of the comparisons made. It can be clearly seen that the cost of commercially available LIBs for use in stationary/standby 125 Vdc systems is still at this time significantly higher than LA and NiCd battery storage. Benefits of smaller size/weight and less frequent/involved maintenance must be balanced with budget expectations.

The author notes that at the time of this writing the number of commercially available LIBs designed to work with 125 Vdc stationary/standby applications is relatively low compared to the same battery chemistries designed for other applications such as BESS and BEVs. This reduces the available pool for input data considered, however, the two systems represented are both from industry leading manufacturers in this young sector. This ensures that the comparison is as even as possible in terms of system reliability.

Battery System Factors - VLA v VRLA v NiCd v LIB

	VLA	VRLA	NiCd	LTO	Super LFP
Capacity (kWh)	24.0	24.0	22.6	25.4	27.0
Cost Factor	1.00	1.07	1.53	4.74	5.79
Footprint Factor	1.00	0.15	0.88	0.92	0.34
Volume Factor	1.00	0.30	1.23	1.56	0.65
Weight Factor	1.00	0.88	0.84	0.75	0.64
Cell Count	60	60	92	576	280

Figure 2 Battery System Factors
See Appendix A for additional information.

X. CONCLUSION

Can traditional LA or NiCd batteries in stationary/standby service be replaced with modern LIBs? Yes, they can, but it is not a simple swap:

1. First, the LIB and the facility/container housing it must be designed to withstand a thermal runaway caused fire and the potentially explosive gases produced by thermal runaway. This can be very costly and is not needed for lead-acid or NiCd battery systems. Do you really want to install a device into your refinery or chemical plant, that even when properly installed and maintained, could start a fire, or initiate a deflagration event?
2. Second, the charging system may need to be replaced or upgraded to properly work with the LIB.
3. Third, the reduction in reliability caused by the devices needed for LIB operation must be considered. Is N+1 redundancy enough? The industry has not yet answered this question and likely won’t, given the different system complexities, needs, and low commercial demand.
4. Fourth, the significant cost differential must be considered. The costs of LIBs may be justifiable in cases where weight and space have significant costs such as in offshore facilities. The cost of LIBs and the associated facility costs do not make LIBs an attractive replacement for LA or NiCd batteries in traditional land-based stationary/standby service, today.

One of the biggest advantages of LIB’s is their high discharge/recharge cycle life. LIB’s have cycle lives in the thousands to over ten thousand discharge/recharge cycles. This advantage offers little to no benefit in stationary/standby applications as these systems do not routinely cycle. Even in locations that could cause stationary/standby cycling there are conventional lead-acid and NiCd cells that can meet those cyclic needs.

XI. ACKNOWLEDGEMENTS

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XIII. VITAE

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APPENDIX A

Battery System Cost Factor, Space, & Weight - VLA v VRLA v NiCd v LIB

Battery System Cost Factor, Space, & Weight - VLA v VRLA v NiCd v LIB					
	VLA	**VRLA**	**NiCd**	**LTO**	**Super LFP**
Capacity (kWh)	24.0	24.0	22.6	25.4	27.0
Length (in)	136.0	25.9	105.0	59.0	48.0
Depth (in)	21.0	16.3	24.0	44.5	20.1
Height (in)	47.5	95.2	66.3	80.8	90.9
Weight (lb.)	3,015	2,662	2,535	2,270	1,932
Volume (in^3)	135,631	40,076	167,076	212,140	87,708
Volume (ft^3)	78	23	97	123	51
Cost Factor	1.00	1.07	1.53	4.74	5.79
Footprint Factor	1.00	0.15	0.88	0.92	0.34
Volume Factor	1.00	0.30	1.23	1.56	0.65
Weight Factor	1.00	0.88	0.84	0.75	0.64
Cell Count	60	60	92	576	280

Notes and Assumptions:

- Battery with Racking/Cabinets - Typical Cost for 200Ah System
- 1.0 Factors Based on Flooded System
- NiCd price includes cost for factory commissioning
- Assumed No Seismic Requirements
- Assumed 125 Vdc, 200Ah System (or next commercially available size)
- Assumed N+1 Redundancy for LTO and LFP Systems (redundant string not considered in capacity calculation)
- LIBs Come With Startup/Installation Required by Supplier