Battery Management System (BMS) Design for Lithium-ion Batteries, A Holistic Approach

holistic, adjective, \hō-ˈlis-tik
Merriam-Webster Dictionary: **relating to or concerned with wholes or with complete systems rather than with the analysis of, treatment of, or dissection into parts**

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Agenda

- Introduction
- Definitions
- What is a Battery Management System
- Requirements
- Design Process
- Verification
- Observations & Lessons Learned
- Conclusion

Introduction

- Due to the benefits of higher specific energy (Wh/kg), energy density (Wh/L) and specific power (W/kg), there has been a vast proliferation in the use of lithium-ion secondary batteries across all industries – consumer, industrial, medical and military/aerospace & defense

- With the improvements in power and energy come safety issues not usually observed with many prior mainstream secondary battery technologies
  - Prior technologies were aqueous based electrolytes which do not burn
  - Organics found in Li+ batteries burn
  - Therefore while fire, smoke and the rare case of spontaneous disassembly were observed in these prior tech's (PbAc, NiCd, AgZn, NiMH, etc.) the effects are greater with Li+ batteries

- While significant, important work is being performed to identify inherently safer cells, lithium-ion secondary batteries are already here and in widespread use

- The purpose of this presentation is to provide the battery designer and procuring agent with the knowledge necessary to arrive at a safe and cost effective lithium-ion battery solution that meets its intended requirements

What's the Problem?

- **There is currently no clear and precise definition for what constitutes a Battery Management System (BMS) for lithium-ion batteries that is universally accepted by all stakeholders, including developers, manufacturers, integrators and users**

- The definitions that do exist, such as the one provided by S9310, are **generic, overly simplistic and imply that there is some one, grand BMS design** (although scalable) that can be used for all lithium-ion batteries

- Consequences are numerous, some of which are:
  - Multiple and often inconsistent BMS interpretations
  - Inconsistent, missing and/or conflicting requirements for batteries, BMS's and systems using batteries
  - **Ineffective battery, BMS and system designs**
    - Do not fully meet the requirements
    - Overly complex or too simple
  - **Point / single application designs**
  - **Cost increases at all levels and phases**
    - Battery cell, battery assembly through system level
    - Design, validation and test for both performance and safety
  - Longer than necessary development time
  - Increased training for users

Terms and Definitions

- Why do we need precise and consistent definitions?

  ANSWER: To avoid confusion, add consistency across platforms, reduce complexity, increase safety and ultimately, reduce cost

Term	Definition
Battery Cell or Cell	The basic electrochemical unit providing a source of electrical energy by direct conversion of chemical energy.[1]
Battery or Battery Assembly	One or more electrochemical cells, electrically connected in series/parallel arrangements to provide the required operating voltage and current levels, including, if any, monitors, controls and other ancillary components (e.g., fuses, diodes), case, terminals, and markings.[1]
System	Group of devices comprised of multiple components, hardware and software one of which may be a battery.
State of Health (SOH)	A measure of a battery (cell or battery pack) to store and deliver electrical energy, compared to its ideal conditions. The units of SOH are percent points with 100% = the battery's conditions match the battery's specifications). **There is no universal definition of SOH**
State of Charge (SOC, %)	**The relative available capacity (%) in a battery.**

NAVY Definition of Battery Management System

- NAVSEA S9310-AQ-SAF-010, Navy Lithium Battery Safety Program Responsibilities and Procedures
  - Appendix A-1, **Definitions. Battery Management System (BMS)** – An **electronic system** designed for a secondary (rechargeable) battery that monitors the charging cycle to protect the individual cells of a battery from overcharging. A BMS may also be used to control/monitor discharge of individual cells in either a primary (non-rechargeable) or secondary (rechargeable) battery. Also known as Battery Monitoring Systems.
  - 4-4.4 BATTERY MANAGEMENT SYSTEM (BMS). **Large form rechargeable batteries must use a battery management system that provides access to information on the performance, cycle-count, age, and condition of the battery.** This BMS may be integral to the battery and include the protections of paragraph 4-4.2 and 4-4.3 above, or the BMS may be an interface to the system the battery is installed in. These guidelines are also recommended for smaller batteries.
  - 4-4.2 **CELL-TO-CELL BALANCING MECHANISMS**. During charging, differences in individual cells may lead to differing voltages in cell groups. Some cells may be undercharged, with a result of decrease in the overall battery capacity. Conversely, some cells may be overcharged, with the result of cell damage, shortening of life cycle, or the creation of safety issues. **In order to achieve a uniform state of charge, consideration shall be given to including a cell-to-cell balancing mechanisms for use during battery charging systems.**
  - 4.4.3 OVERVOLTAGE PROTECTION. Rechargeable batteries shall have integrated overvoltage (over-charge) protection. **These protections must disconnect the battery from the charging source. Disconnect must be automatic and not require operator action.**

BMS - Benefits of a Clear Definition

- Reduced **nonrecurring cost**, those associated with the design and validation of batteries and battery systems
- Reduced battery and system **development time**
- **Standardize interfaces** to promote **cross compatibility** of batteries and equipment expected to reduce recurring costs through
  - Increased production of fewer types of batteries
  - “Black box” designs fostering competition between multiple suppliers
- Reduce burden on users
- **INCREASED SAFETY!!!**
  - **Identification of appropriate safety concerns/features**
  - **Elimination of failure modes introduced by unnecessary features**
- In order to truly realize these benefits one must understand and define the **functions** and **components** of a BMS
  - **Functions** are what it needs to do
  - **Components** are the physical or tangible parts and pieces
  - A specific function may require multiple components
  - Similarly, a single component may be capable of performing multiple functions

What are the Functions of a BMS

- Charge and discharge control
- Control of power interface(s)
- Provide telemetry from battery and/ battery cells such as
  - Voltage
  - Current
  - Temperature
  - Pressure
  - Operational status
  - Failure status
  - SOC
  - SOH
  - Fault History
- Fault protection (fault tolerance and/or redundancy)
  - Overvoltage
  - Overcharge
  - Over-discharge
  - Current Limiting
  - Over-temperature
  - Over-pressure
  - Leakage
  - Chassis Shorts
- **Cell Balancing**
- **Safety features**
- Provide communication interface(s)
- Store performance data
- Monitor battery performance
- Determine battery state of health (SOH)

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What Components Might Comprise a BMS

- The components comprising a BMS are determined largely by the battery capacity and required functions.
  - Comprehensive system design is **absolutely critical** for large batteries and complex point designs
  - **Safety** considerations generally become more of a factor as the size of a battery increases in terms of capacity and output voltage
- Obvious components
  - Electronics
  - Software/Firmware
- The not so obvious
  - Battery cell
    - Chemistry
    - Internal safety features
    - Package Configuration and Format
  - Mechanical and electrical interfaces (internal and external)
  - **Physical packaging of the battery assembly**
  - System using the battery
  - Mechanical and packaging considerations typically overlooked
  - Storage

Requirements! Requirements! Requirements!

- Where does the design process start?

  Answer: With the requirements of course!
- Requirements are the vehicle through which specifications are communicated
- **The responsibility for establishing and maintaining requirements belongs primarily to the "procuring agent"** and **not** the "producer" **(i.e. top → down)**
- Requirements should be **comprehensive**, **reasonable**, **realistic, clear** and **precise to assure** arriving at a useable, cost effective product in a reasonable period of time
- Requirements Flow
  - The **top → down** flow of requirements should be maintained to the greatest extent possible.
  - There will almost always be some bottom → up flow of requirements, particularly during early phases of development
    - When these instances arise, they should be brought to the attention of the necessary upper level agent(s) for adjudication as quickly as possible
    - Implementation of these requirements should only occur after agreement has been reached with the appropriate upper level agent(s)
  - Failure to adhere to these simple rules of thumb often leads to **unnecessary** and **unplanned** redesign which in turn increases cost and schedule
- Requirements must be **verifiable** by at least one (preferably two or more) of the following methods:
  - Analysis
  - Inspection
  - Test

If a requirement can't be verified it doesn't belong!!!

Things to Remember Regarding Requirements

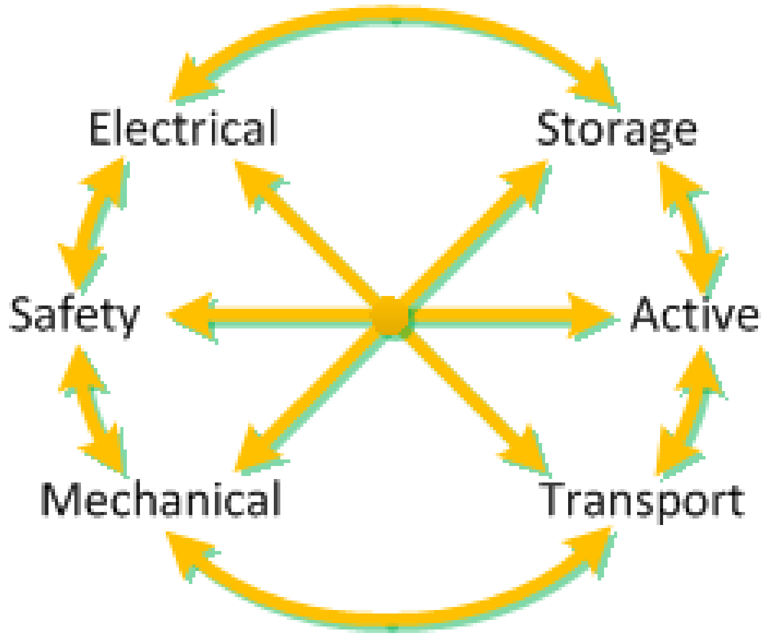
- All requirements are **NOT** created equal!
  - Establishing a hierarchy of the requirements can be very beneficial.
  - Recommended ranking criteria for requirements.
    - Safety
    - Performance (ex. capacity, voltage range, etc.)
    - Cost
    - Bells & Whistles
- Not all functions are necessary or required (ex. cell balancing)
- Most requirements can be met through multiple implementations. When multiple options exist, determine which makes the most sense based on cost, safety, reliability, maintenance, manufacturing, etc.
- Not all requirements need to be achieved within the battery.
  - Battery charger
  - Cell balancing circuitry
- "***Better is the enemy of good enough!***" - attributed to Voltaire

"***Learn it. Know it. Live it!***" - *Fast Times at Ridgemont High*

Requirements Wheel

- Battery requirements fall into three basic categories
  - Electrical
    - Voltage, current, power, energy, etc.
    - Fault tolerance & redundancy
    - State of Health (SOH)
    - Electrical interfaces
  - Mechanical
    - Physical dimensions / envelope
    - Thermal Performance
    - Mechanical Interfaces
    - Environmental Constraints
  - Safety
    - Human
    - Environmental
    - System

- Battery requirements address three basic states of hardware
  - Storage
  - Active / in use
  - Transportation



BMS Design Considerations

- Identify the functions **required** of the BMS requirements
  - Safety
  - Performance
  - Cost (recurring, nonrecurring, maintenance, repair, etc.)
- Identify failure modes at cell and battery assembly levels.
- Determine level(s) at which these functions or features can or will be implemented (cell, battery assembly or system)
- Define interface requirements
  - Electrical
  - Mechanical / Thermal
- Determine whether standard battery formats (18650, prismatic, pouch, etc.) are viable or whether a custom approach is necessary
- Generate a **requirements matrix** and reference it early and often, aggressively and track changes!
- Recognize up front that this will be an iterative process!
  - 1080 Design Process, expect at least 3 iterations
  - Hold peer reviews early, starting at the conceptual phase
  - Reassess continually but not to the point of paralysis

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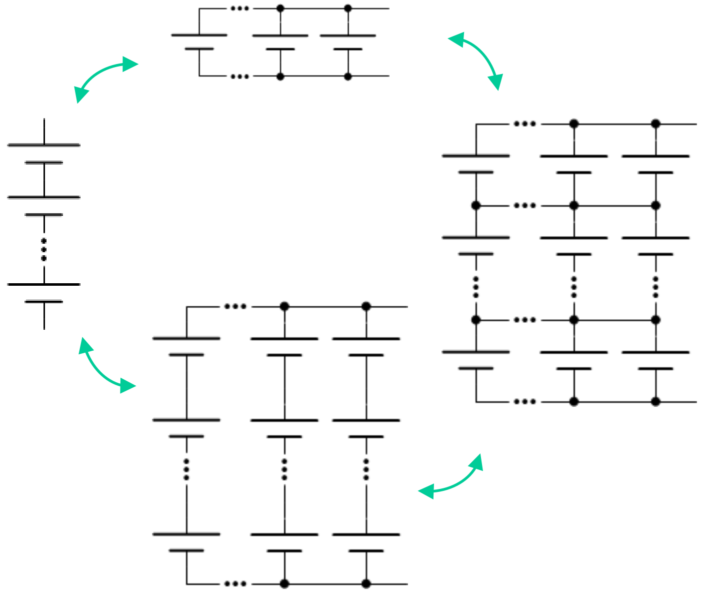
Trade Studies

- Battery Cells
  - Energy vs Power
  - Chemistry
  - Small vs large format
  - Internal safety features
- Cell configuration
  - Series vs parallel
  - Strings vs matrix
- Smart vs dumb
- Charge Management Method
- Hardware vs software
- Fault tolerance/redundancy
- Failure mitigation techniques
  - Battery cell vs battery assembly
- Recurring vs nonrecurring cost
- Cost vs performance/complexity
- Complexity vs reliability
- Cross compatibility

$LiFePO_4$ $LiCoO_2$ LiNiMnCoO2 $LiMn_2O_2$ $Li_4Ti_5O_{12}$ $LiNiCoAlO_2$ NiMH Lead Acid



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Design Verification

- Analysis
  - Electrical Worst Case Analysis (circuit performance)
  - Electrical, Electronic and Electro-mechanical Parts Stress Analysis
  - **Fault Tree Analysis (FTA)**
  - **Failure Mode Effects and Criticality Analysis (FMECA)**
  - Thermal Analysis
  - Mechanical Stress Analysis
  - **Software verification**
- Inspection
  - Parts
  - Workmanship
  - Processes
- Test
  - Electrical Performance
  - Mechanical & Environmental Performance
  - **Safety**
  - **Software**

Lessons Learned & Observations - Requirements

- Existing standards do not adequately define safety requirements for batteries
- Specifications written stipulating implementations, goals and/or “desirements” instead of hard & fast requirements
- Loopholes and conflicting requirements in existing standards
- Requirements not adequately developed by users / lack of adequate systems engineering
- Excessive supplier driven requirements (bottom → up instead of top → down flow)
- Beware calls for **“graceful degradation”**
  - The gradual decrease in battery capacity over life and cycling is and example of graceful degradation
  - The ability of a battery or system to continue to operate after suffering a failure is an example of **fault tolerance**

Lessons Learned & Observations - Design

- **Understanding failure modes and hazards of all components is essential to producing a safe battery design**
- Lack of systems engineering
- Trade studies lack quality or are missing all together (lacking objectivity)
- **Inadequate design/peer review**
  - Improper or missing skill sets
  - Insufficient experience
  - Reviews held too late in design process
- All too often a design starts with a specific component, particularly a specific battery cell (solution looking for a problem)
- Overly complex designs leading to poor/reduced reliability and single use designs
- Poor implementation of **modularization**
- **Design for test** (hardware and software)**!!!**

Lessons Learned & Observations - Verification

- Substandard design verification practices (analysis and test)
- **Design for test!!!**
- Insufficient sample sizes for performance and safety verification
- Applicability of tests are questionable, not clearly defined

Conclusion

- A BMS is **NOT** simply a set of electronics used to maintain battery state of charge and/or monitor state of health and subscribing to that view can lead to ineffective battery designs which do not meet requirements or cost goals and are application specific
- A BMS is the system of components, functions and features necessary to meet the performance, environmental and safety **requirements** of the battery and the system within which it is being used over the expected life of the product
- The scope, breadth and complexity of the BMS should be directly dependent upon the necessary battery requirements and not on **"extra"** features
- The BMS can permeate all levels of the battery and system using it, (e.g., battery cells, electronics, software, mechanical design) as well as have external components (e.g., storage, chargers) and therefore it is imperative that thorough system engineering is performed
- **There is no "one size fits all" BMS**

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Backup Slides

Terms and Definitions

Term	Definition
Failure	The event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified.[5]
Failure Rate	The total number of failures within an item population, divided by the total number of life units expended by that population, during a particular measurement interval under stated conditions.[5]
Failure in Time Rate (FIT)	For a device, the number of failures that can be expected in one billion (10^9) device-hours of operation. (E.g. 1000 devices for 1 million hours, or 1 million devices for 1000 hours each, or some other combination.) This term is used particularly by the semiconductor industry.
Fault Tolerance	The property that enables a system to continue operating properly in the event of the failure of (or one or more **faults** within) some of its components.[5]
Graceful Degradation	The ability of a computer, machine, electronic system or network to maintain limited functionality even when a large portion of it has been destroyed or rendered inoperative. The purpose of graceful degradation is to prevent catastrophic failure.
Mean Time Between Failure (MTBF)	A basic measure of reliability for repairable items: The mean number of life units during which all parts of the item perform within their specified limits, during a particular measurement interval under stated conditions.[5]
Redundancy	The existence of more than one means for accomplishing a given function. Each means of accomplishing the function need not necessarily be identical.[5]
Reliability	The probability that an item can perform its intended function for a specified interval under stated conditions.[5]

Terms and Definitions (continued)

Term	Definition
Hazard Analysis	The process of recognizing **hazards** that may arise from a system or its environment, documenting their unwanted consequences and analyzing their potential causes.
Hazard	A "Condition, event, or circumstance that could lead to or contribute to an unplanned or undesirable event." Examples: Fuel oil spill, personal injury, fire, property damage.
Causal Factors	Events, actions, conditions and circumstances that may leading to a given consequence (e.g., hazard)
Risk Analysis	The process of defining and analyzing the dangers to individuals, businesses and government agencies posed by potential natural and human-caused adverse events. (highly subjective)
Failure Mode Effects and Criticality Analysis (FMECA)	Failure mode, effects and criticality analysis (FMECA) is a reliability evaluation/design technique which examines potential failure modes within a system and its equipment, in order to determine the effects on equipment and system performance. Each potential failure mode is classified according to its impact on mission success and personnel/equipment safety.[3] It is a **bottom-up**, inductive analytical method which may be performed at either the functional or **piece-part level**.
Fault Tree Analysis (FTA)	A **top down**, deductive failure **analysis** in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. Commonly referred to as a Fishbone Analysis.

Sample Cell Chemistry Characteristics

Chemistry	Voltages	Specific Energy (Wh/kg)	Charge Rate	Discharge Rate	Life Cycle	Thermal Runaway	Comments
Lithium Iron Phosphate (LiFePO4)	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell	90–120Wh/kg	1C typical, charges to 3.65V; 3h charge time typical	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)	1000–2000 (related to depth of discharge, temperature)	270°C (518°F) Very safe battery even if fully charged. One of safest Li-ions.	Very flat voltage discharge curve but low capacity. Elevated self-discharge.
Lithium Cobalt Oxide (LiCoO2)	3.60V nominal; typical operating range 3.0–4.2V/cell	150–200Wh/kg. Specialty cells provide up to 240Wh/kg.	0.7–1C, charges to 4.20V (most cells); 3h charge typical. Charge current above 1C shortens battery life	1C; 2.50V cut off. Discharge current above 1C shortens battery life	500–1000, related to depth of discharge, load, temperature	150°C (302°F). Full charge promotes thermal runaway	Very high specific energy, limited specific power. Cobalt is expensive. Serves as Energy Cell.
Lithium Manganese Oxide (LiMn2O2)	3.70V (3.80V) nominal, typical operating range 3.0-4.2V/cell	100-150Wh/kg	0.7-1.0C typical, 3C max, charges to 4.20V (most cells)	1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off	300-700 (DOD and temperature dependent)	250C, high charge promotes thermal runaway	High Power but less capacity: safer than Li-cobalt
Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or NMC)	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher	150–220Wh/kg	0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life	1C; 2C possible on some cells; 2.50V cut-off	1000–2000 (related to depth of discharge, temperature)	210°C (410°F) typical. High charge promotes thermal runaway	Provides high capacity and high power. Serves as Hybrid Cell.

Sample Cell Chemistry Characteristics

Chemistry	Cell Voltages	Specific Energy (Wh/kg)	Charge Rate	Discharge Rate	Life Cycle	Thermal Runaway	Comments
Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$, or NCA)	3.60V nominal; typical operating range 3.0–4.2V/cell	200-260Wh/kg; 300Wh/kg predictable	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells	1C typical; 3.00V cut-off; high discharge rate shortens battery life	500 (related to depth of discharge, temperature)	150°C (302°F) typical, High charge promotes thermal runaway	Shares similarities with Li-cobalt. Serves as Energy Cell.
Lithium Titanate, ($Li_4Ti_5O_{12}$, or LTO)	2.40V nominal; typical operating range 1.8–2.85V/cell	70–80Wh/kg	1C typical; 5C maximum, charges to 2.85V	10C possible, 30C 5s pulse; 1.80V cut-off on LCO/LTO	3,000–7,000	One of safest Li-ion batteries	Long life, fast charge, wide temperature range but low specific energy and expensive.
Nickel Metal Hydride (NiMH)	1.25V nominal, operating range 1.5-0.90V/cell	60-120Wh/kg	0.1-0.5C	5C	500-2000 cycles		
Lead Acid	2.0 nominal, operating range 2.10 -1.95V/cell	30-50Wh/kg	0.3C	5C	500-800 cycles		