



IEEE Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications

IEEE Power and Energy Society

Developed by the
Energy Storage and Stationary Battery Committee

IEEE Std 2686™-2024

STANDARDS

IEEE Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications

Developed by the

Energy Storage and Stationary Battery Committee
of the
IEEE Power and Energy Society

Approved 26 September 2024

IEEE SA Standards Board

Abstract: Information and recommendations on the design, configuration, and interoperability of battery management systems in stationary applications is included in this recommended practice. The battery management system is considered to be a functionally distinct component of a battery energy storage system that includes active functions necessary to protect the battery from modes of operation that could impact its safety or longevity. Recommendations on how to configure a battery management system to protect a given battery type in each application environment are provided. Lastly, recommended communication structures and data models that help support interoperability and cybersecurity are stipulated. A comprehensive list of best practices around the design and integration of battery management systems that protect the safety and longevity of batteries in energy storage applications is developed as a result.

Keywords: batteries, battery degradation, battery management system, battery safety, BMS, distributed energy technologies, energy storage, IEEE Std 2686™, interoperability, SOC, SOH, state-of-charge, state-of-health

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Introduction

This introduction is not part of IEEE Std 2686-2024, IEEE Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications.

New batteries have been developed recently that provide high performance but require precise management. Precision battery management can be costly itself, so it is important to match the features of a battery management system to what is needed to protect a given battery in its application environment. Further, in the past years there have been fires in stationary battery systems that have, rightly or not, been partially attributed to the failure or poor design of battery management systems. Without established best practices in battery management design, industry confidence in its ability to prevent such accidents could begin to erode. Lastly, the battery management system can play an integral role providing accurate and up-to-date state and diagnostic information to the energy storage management system (ESMS), maintenance personnel, and, in the case of an accident, first responders. However, without basic standardization of interoperability, information exchange, information models, and protocols to streamline system integration, these capabilities are difficult and costly to realize.

This recommended practice describes battery management fundamentals including best practices in design and coordination with an ESMS. This document has been developed in close collaboration with industry experts on ESMS. It describes the hardware and software architectures commonly used in battery management and provides a list of battery management functions that can be applied to different batteries in different applications. It provides recommendations on how to configure a battery management system to protect a given battery type in each application environment. Lastly, it stipulates recommended communication structures and data models that help support interoperability and cybersecurity. The result is a comprehensive list of best practices around the design and integration of battery management systems that protect the safety and longevity of batteries in energy storage applications.

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IEEE Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications

1. Overview

1.1 Scope

This recommended practice includes information on the design, configuration, and interoperability of battery management systems (BMSs) in stationary applications. This document considers the BMS to be a functionally distinct component of a battery energy storage system (BESS) that includes active functions necessary to protect the battery from modes of operation that could impact its safety or longevity.

This document covers battery management technologies, configuration by application and battery type, and interoperability with other systems. Technologies include battery management peripheral devices and subsystems, balancing methods, sensor types and placement, physical and software architectures, and battery management functions. Configuration includes both grid-supporting and non-grid-supporting applications and specific recommendations for the following battery types: lithium-ion, flow, sodium- β , and alkaline zinc-manganese. General recommendations applicable to other battery types are provided. Interoperability recommendations include guidance such as minimum measurement accuracy and state-of-charge reporting standards, communications including information models and error reporting, and cybersecurity including access control and software update management best practices.

Transportable energy storage systems that are stationary during operation are included in this standard. This document does not cover BMSs for mobile applications such as electric vehicles; nor does it include operation in vehicle-to-grid applications. Energy storage management systems (ESMS), which control the dispatch of power and energy to and from the grid, are not covered.

1.2 Purpose

Well-designed battery management is critical for the safety and longevity of batteries in stationary applications. This document aims to establish best practices in the design, configuration, and integration of BMSs used in energy storage applications.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Definitions, acronyms, and abbreviations

2.1 Definitions

For the purposes of this document, the following terms and definitions apply. IEEE Std 1881™, IEEE Standard Glossary of Stationary Battery Terminology [B29], or the *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.^{8,9,10}

active cell balancing: The redistribution of energy among cells using switching electronics in a battery to reduce inequalities in voltage or state of charge.

alarm: A general term for a fault or error reported to the user.

battery management system (BMS): A system that includes active functions necessary to control activities such as charging, discharging, thermal management, and safety.

NOTE—A BMS uses application-specific algorithms to manage a rechargeable battery by monitoring its state, calculating secondary data, reporting that data, protecting the battery, controlling its environment, and/or balancing it.¹¹

cell balancing: A process by which inequalities in voltage or state of charge (SOC) among cells in a battery are corrected.

charge imbalance: Inequalities in state of charge (SOC) between cells in a battery.

error: A loss of data or control integrity such that a violation of an interrupt constraint could not be identified or prevented.

NOTE—An error generally refers to an issue with the BMS itself such as a broken sensor, contactor, or subroutine that could lead to an unsafe or accelerated degradation state in the battery.

fault: A violation of an interrupt constraint.

NOTE—A fault generally refers to a condition that is unsafe or results in accelerated degradation as defined by the interrupt constraints identified in the managed battery.

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

⁸IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

⁹The numbers in brackets correspond to those of the bibliography in Annex E.

¹⁰*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹¹Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

float service: *See also: standby service.*

interrupt constraints: Limits on battery states that are imposed by actively stopping battery current.

operational constraints: Limits on battery states that are imposed by dynamically restricting operation.

NOTE—Dynamic restriction means to restrict without stopping. Operational constraints are the boundaries of the battery’s allowable operating window relative to conditions such as SOC and temperature. A common example of an operational constraint is a maximum speed governor in a commercial vehicle.

passive cell balancing: The dissipation of energy from cells into passive circuit components or through electrolysis to reduce inequalities in voltage or state of charge (SOC) among cells in a battery.

standby service: Operating mode of a dc system in which it is anticipated that a battery or other energy storage device will spend the majority of the time on float charge with infrequent discharge. *Syn: float service.*

switch: A device designed to close or open, or both, one or more electric circuits. In this standard, the term “switch” does not imply that the device has interrupting capability. A switch may not be capable of making or breaking current.

thermal runaway: A self-sustaining and uncontrollable rise in temperature resulting in a failure of a cell, unit, or battery.

NOTE—The thermal runaway event will remain self-sustaining until the available energy within the cell, unit, or battery is depleted.

voltage imbalance: Inequalities in voltage between cells in a battery.

warning: The reporting of a violation of an operational constraint.

NOTE—The warning should stay in place for as long as the violation persists. A warning may result in the adjustment of an operational constraint (e.g., high temperature warning reducing operational charging current constraint).

2.2 Acronyms and abbreviations

BC	balancing circuit
BESS	battery energy storage system
BMS	battery management system
BOL	beginning of life
CC	constant current
CP	constant power
CSA	Canadian Standards Association
CV	constant voltage
DOD	depth of discharge
EMI	electromagnetic interference
EOL	end of life
ESMS	energy storage management system
FMEA	failure modes and effects analysis
FSS	fire suppression system
HVAC	heating ventilation and air conditioning
IEC	International Electrotechnical Commission

ISO	International Organization for Standardization
LFL	lower flammable limit
LFP	lithium iron phosphate
MOSFET	metal-oxide-semiconductor field-effect transistor
MSDS	material safety data sheet
OSHA	Occupational Health and Safety Administration
PCS	power conversion system
PSOC	partial state of charge
SOA	safe operating area
SOC	state of charge
SOH	state of health
TLS	transport layer security
UL	Underwriters Laboratories
UPS	uninterruptible power supply

3. Battery management fundamentals

3.1 General

The role of the BMS in BESSs is to enforce a battery's safe operating area (SOA). Here the word "safe" is not intended to indicate that the battery is intrinsically safe when operating within the SOA (it is not), but that operation within the SOA is "safe by design". The IEEE Standard Glossary of Stationary Battery Terminology [B29] defines BMS as:

A system that includes active functions necessary to control activities such as charging, discharging, thermal management, and safety.

This definition states that battery management is an "active" process, implying that it collects information about the batteries being managed, makes decisions using that information, and effectuates its decisions with control action. Control actions can refer to communication to other devices such as the ESMS or power conversion system (PCS) but also include the operation of cell-balancing hardware (see 4.2.6) and the actuation of circuit-interrupting devices (see 4.2.8.3) to protect the battery from hazardous operation. This active role distinguishes a BMS from a battery monitoring system covered by IEEE Std 1491™ [B20]. Additionally, a BMS that protects only a discrete portion of a system elevates warnings and alarms to a server BMS or ESMS, which are then able to appropriately restrict operation at the system level. For example, violation of an interrupt constraint in one string will cause that string's BMS to trip the string and report this change to the server BMS, which will dynamically adjust the system operational constraints accordingly. Note that a BMS may include functions that trigger or request charge or discharge. Examples of this include periodic equalization charge in lead-acid systems, or dendrite stripping cycles in zinc-bromine flow battery systems. The purpose of battery management is to maintain battery safety and longevity and, therefore, actions taken by a BMS generally supersede economic concerns or grid conditions, though not always (see 5.2.3.2.1).

The terminology of battery management is flexibly applied to a broad range of hardware and software. The specific term BMS is sometimes used to refer to an integrated circuit or a network of sensors, electronics, and micro-controllers. While this document is aimed primarily to support a network of sensors, electronics, and micro-controllers, certain recommendations and principles can and should be applied to all BMSs. The active decision-making functions may be performed by a single, centralized process or be distributed into modules.

This document uses the term battery management function to refer to any process intended to enforce an operational or interrupt constraint on one or more battery cells. A BMS is made up of a collection of sensors to collect data from a battery, actuators to protect a battery, and battery management functions to automate protective actions. The term battery management function does not detract, limit, or change the definition of BMS but it enables a more precise discussion of the engineering best practices involved in designing systems that manage battery operations. Battery management functions enforce constraints on voltage, current, temperature, and many other factors depending on the chemistry and application.

It should be noted that operational constraints are implemented to extend the life of the battery but are not safety related. They may be adjusted in real time based on states (e.g., limited charge current at low temperature), time (e.g., short-term power rating), operational mode (e.g., grid emergency), or operator input (e.g., extreme energy price).

Safety-related interrupt constraints are implemented by opening a circuit interrupt device (see 4.2.8.3) to reduce the risk of unacceptable outcomes such as early battery failure or fire.

3.2 Cell safety

A notional example of an SOA for a given battery cell is shown in Figure 1. The figure shows safe ranges of voltage and temperature; however, this figure could be extended to state of charge (SOC), current, pressure, and many other factors depending on battery type. The BMS enforces its operational and interrupt constraints within an area inside the SOA depending on its application (see 5.2). At any time, each individual cell being managed by a BMS has a set of states within the SOA. Some combinations of states, for example, high voltage and temperature, could lead to accelerated degradation while others could lead to the development of a safety hazard. The boundaries between these areas are often gradual or uncertain. The SOA is a defined boundary within which the cells are known to operate safely.

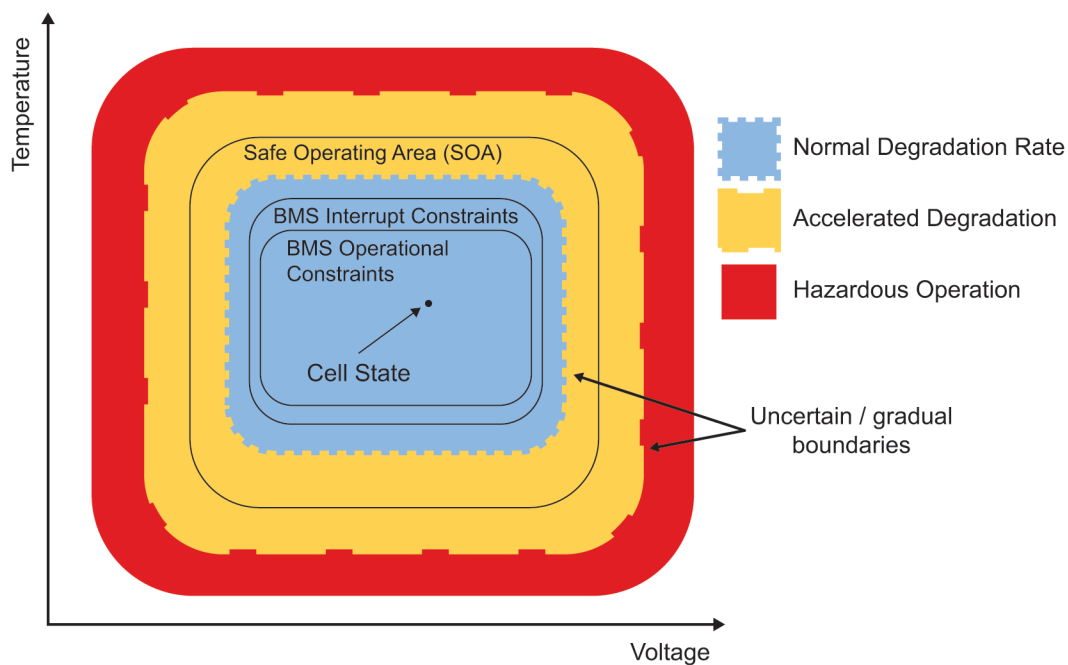


Figure 1—Example steady-state SOA enforced by a BMS

The effectiveness of enforcing an SOA is further complicated when the measurements of the battery's state is inaccurate or uncertain (see 6.2.3). State uncertainty is accounted for by adding a buffer to the operational and interrupt constraints such that the cells are very unlikely to violate the SOA. In addition, batteries often have short-duration ratings that temporarily stretch the boundaries enforced by the operational and interrupt constraints (see 5.2.2.4). BMSs are also responsible for managing batteries containing many cells, each with its own set of conditions and states. Manufacturing tolerances cause cell SOC's to drift apart over time leading to variance in voltages as well. Figure 2 shows an example of a cluster of states of a battery operating within its recommended operating area. The BMS is responsible for keeping the entire cluster within the safe operation area by monitoring the state of all impacted components within its protection zone (see 3.5.2).

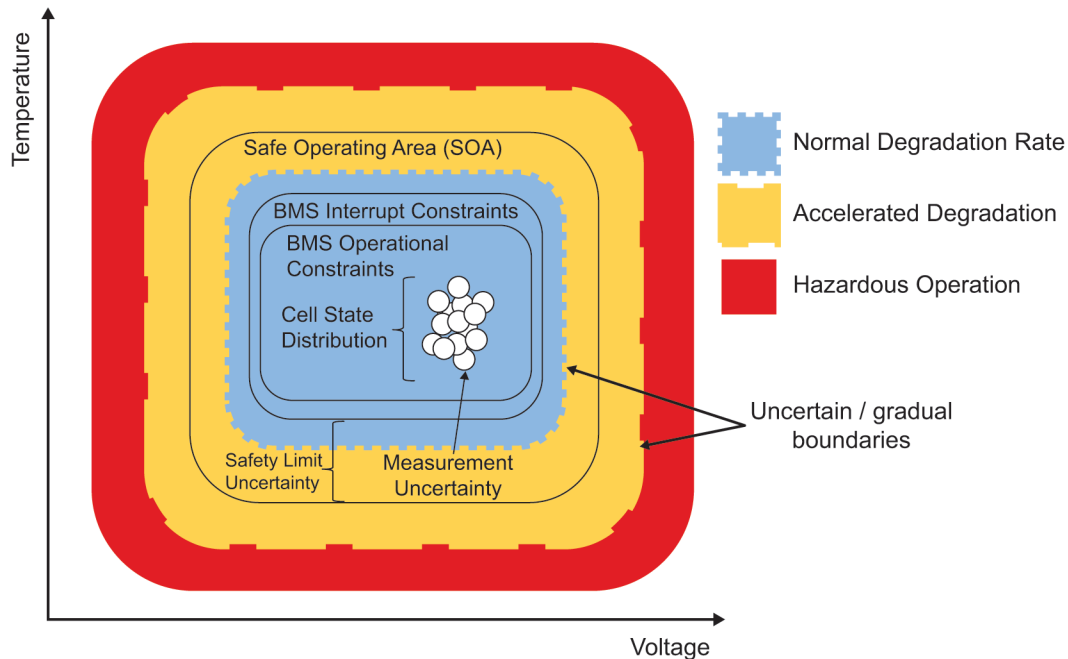


Figure 2—SOA of a string of cells or modules with variance and uncertainty

3.3 Cell longevity

In addition to keeping cells within the SOA, a BMS may be configured to prolong the useful life of the battery. This is done by further restricting operation within the SOA to reduce normal degradation. A BMS can be configured to improve longevity but this function is also commonly performed by the ESMS (see 3.4 and Annex A). For example, a battery in a standby application (see 5.2.3.2) has flexibility in how it recharges after an outage. The BMS in this example may be configured with a reduced maximum charge rate operational constraint.

Further restricting the operational constraints for longevity should only be done in cases where a battery has a specified design life or warranty life that cannot be achieved through less restricted operation. The degradation impacts of operational decisions such as the charge rate, discharge rate, ambient temperature, and DOD, should be communicated to the user. In cases where the ESMS controls operation to balance battery life with economic factors (see 3.4), the BMS should not be configured to prolong the useful life of the battery.

Battery manufacturers sometimes list the same battery under multiple model numbers to avoid including the complex tradeoffs of performance and life in specification sheets. For example, model X will be listed as having a maximum charge rate of 20 A but a cycle life of only 1000 cycles and model Y will have a maximum charge rate of 10 A and a cycle life 3000 cycles, without any physical or chemical difference between the

models. The BMS for the model Y cells will enforce a maximum charge current of 10 A, even though they could be safely charged at 20 A, to prolong the life of the battery in its intended application. The SOA for both cells is limited to a 20 A charge rate, but the operational window is different.

3.4 BMS-ESMS interaction

An ESMS can be responsible for making charge and discharge decisions for a BESS. To make these decisions, the ESMS needs specific information about the battery's states and operational constraints from the BMS. An example diagram for how a BMS and ESMS may be configured to operate together is shown in Figure 3. The BMS collects and processes voltage, current, and temperature data from the individual cells and modules. Aggregate BMS data (see 4.2.4) are supplied to the ESMS, providing up-to-date information about the battery's states and operational constraints. Structured and standardized communication channels allow the BMS to be interoperable between different ESMSs. See 6.3 for recommendations on interoperability of the general information and control bus.

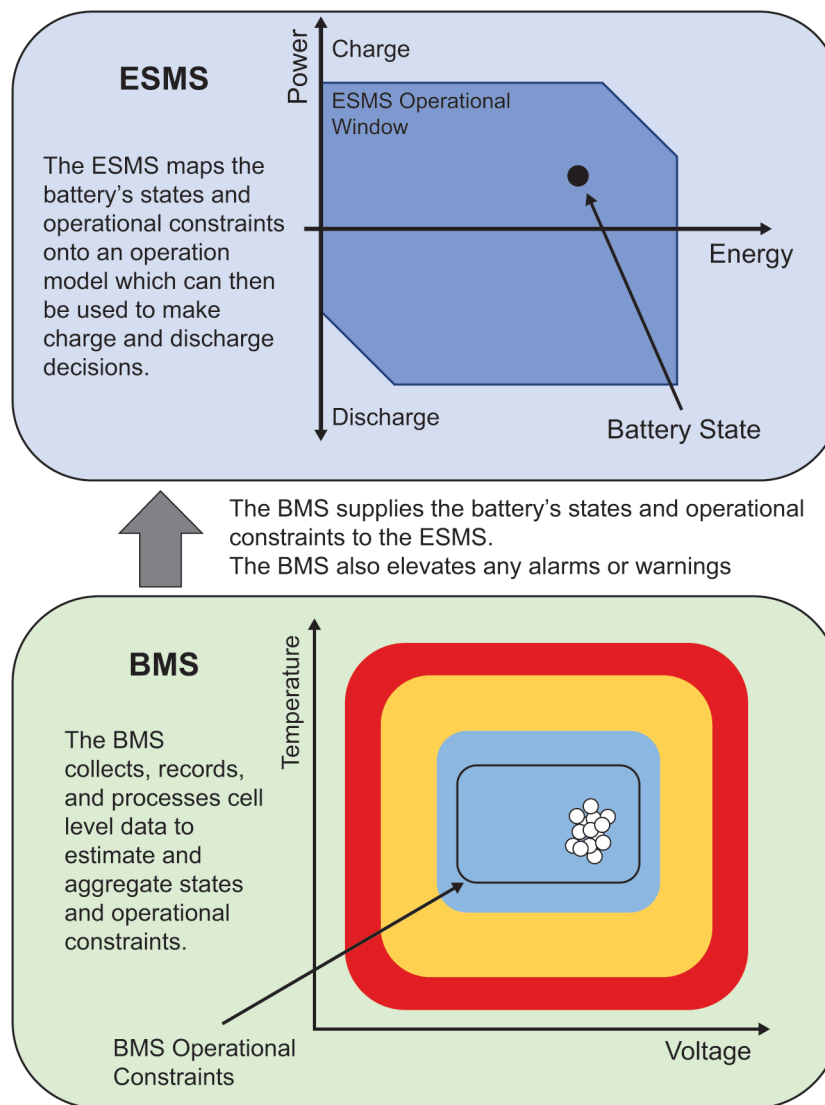


Figure 3—Illustration of BMS-ESMS interactions

The ESMS operational window utilizes as much of the BMS operational window as possible, but it commonly needs to ignore or linearize states like cell voltage spread or temperature. In cases where the ESMS makes charge and discharge decisions that balance battery life with economic factors, the BMS operational constraints should be configured to be as large as possible within the SOA. In cases where the ESMS relies on the BMS to achieve the battery's design life (see 3.3), the BMS operational constraints should be configured to an area within which the battery's rate of degradation is constrained, which may be substantially smaller than the SOA.

3.5 BMS design and/or integration process

3.5.1 General

Subclause 3.5 outlines the recommended process to design or integrate a BMS on a specific battery in a specific application. Following this process helps prevent failures to enforce safety limits effectively and avoid the increased cost of redundant protective devices.

The design of a BMS starts with the requirements based on battery type and the intended application. The requirements for a nickel-metal-hydride battery in a telecom application are very different from a Li-ion system supplying grid services. The design should include a list of specific battery management functions. These functions are then executed by specific hardware and software. BMS devices, which are the hardware and software components implementing BMS functions, should have overlapping responsibilities for redundancy but care should be taken to coordinate the overlap priority to reduce nuisance tripping. Nuisance tripping can occur when a protection actuates out of order. For example, a battery string could have a high voltage cell on charge that causes the whole string to trip offline rather than the PCS simply reducing charge current properly. The assignment of BMS functions and the responsible devices or subsystems is referred to as a protection coordination scheme.

3.5.2 BMS operation protection coordination

The purpose of protection coordination is to design a BMS to enforce the operational and interrupt constraints with appropriate timing, coordination, and redundancy for every component. Put another way, protection coordination is a process to make sure that there are no holes, gaps, or conflicts in the battery's SOA as implemented by the BMS. The physical architecture of a BMS (see 4.3) defines the type and protection performed by various subcomponents of the BMS. Often protection is divided into separate zones, which are defined by physical groupings of cells and their managing devices. Constraints are enforced in a specified protection order depending on their zone. A protection zone encompasses all batteries and cells within the area the device controls. Devices are the specific hardware and software responsible for protecting the battery. The managed value is a dimension of the SOA (e.g., voltage or temperature) for a given battery. For voltage, current, and charge, the zones are the circuits that are interrupted by the operation of a circuit interrupt device. For temperature or other environmental factors, zones refer to the set of batteries that are affected by the operation of specific fans or that are within specific enclosures. The protection order refers to the sequence in which the devices are designed to actuate control on the same managed value within the same zone (e.g., interrupt the same circuit).

Protection order may be coordinated by the magnitude of violation, the duration of violation, or both. For interrupt constraints, the protection order should maximize system reliability by coordinating the BMSs with smaller protection zones to act before those with larger protection zones. This means that the fewest cells are interrupted when a limit violation is detected. Operational constraints should be set to not trigger interrupt constraints during normal operation. For operational constraints, the order of actuation should increase system efficiency and reduce the downtime of batteries by coordinating the BMSs with smaller protection zones to act before those with larger protection zones. System efficiency, in contrast to the round-trip efficiency from charge and discharge, is a function of how much energy it takes to enforce operational constraints. Using high cell temperature as an example, module fans should act first (e.g., at 30 °C) to cool the cells, followed by the enclosure cooling system (e.g., at 35 °C), followed by the high module temperature interrupt (e.g., at 45 °C).

A simple example of protection coordination for a single-string, lithium-ion battery system in a grid-supporting application is shown in Table 1 and Figure 4. See 5.3.2 for the full list of BMS functions recommended for lithium-ion batteries. This partial protection scheme shows five BMS functions: cell voltage management, string voltage management, current management, module temperature management, and charge management. Cell voltage and module temperature measurements are collected by the module BMS while current measurements are collected by the string BMS. The PCS independently collects the string voltage and the string current and implements feedback control to actuate power setpoints provided by the ESMS. The module BMS is configured to trigger an interrupt (see 4.2.7) based on cell voltages and module temperatures while the string BMS interrupts based on string level voltage and current. The mid-string fuse is sized to open the circuit under short-circuit conditions where the circuit interrupt devices may be unable to actuate. Module fans may be activated by the string BMS based on maximum temperature or temperature differential, but cell temperature is also controlled by the heating, ventilation, and air conditioning (HVAC).

Table 1—Example of a protection coordination scheme

BMS Functions ^{1,2,3}	Module BMS	String BMS	Mid-String Fuse	PCS	HVAC	ESMS
	Implements control through circuit interrupt device	Operates on device physics	Implements control through sensor/state feedback			
Voltage management ^c	Σ , I1					
Voltage management ^s		Σ , I1		Σ , O1		
Current management ^s		Σ , O2, I1	I2	Σ , O1		
Temperature management ^m	Σ , O1, I1				O2	O3
Charge management ^s		Σ				O1

¹O# - operational constraint. This device has control of the managed value. The # indicates the order that the devices should act when controlling the managed value.

²I# - interrupt constraint. This device has a designated responsibility to trigger the circuit interrupt in its zone if it detects a limit violation. The # indicates the order that the devices should act.

³ Σ - sensor. This device collects and stores sensor measurements of the managed value.

^cmanagement function implemented on each battery **cell** in the system.

^smanagement function implemented on each battery **string** in the system.

^mmanagement function implemented on each battery **module** in the system.

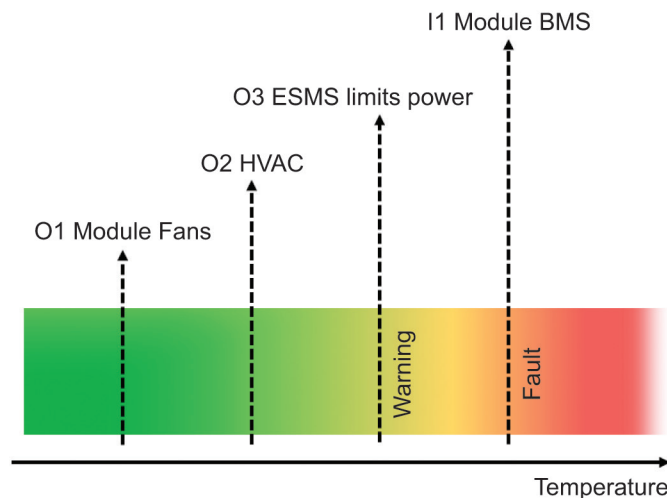


Figure 4—Illustration of example protection coordination for temperature management

The ESMS is the primary controller for charge and discharge power commands in grid-supporting applications (see 5.2.2). These power commands are limited by the available power of the battery system. While the PCS controls the current within the normal operating window, the string BMS overrides that control at temperature or SOC extremes. At its maximum charge, or when a module BMS detects a high cell voltage, the system's available charge power is reduced to zero. At its minimum charge, or when a module BMS detects a low cell voltage, the system's available discharge power is reduced to zero. No device implements an operational constraint on cell voltage because the module BMS provides cell balancing through voltage imbalance management (see 4.5.5.4). When a module BMS detects a high module temperature, the available charge and discharge power is reduced to prevent excess heat generation. A designer could change the schema to add an extra level of control (O4) to the ESMS to discontinue PCS operation. Calculation of available charge and discharge power may be performed by the BMS or the ESMS.

Developing the protection coordination table for a specific battery system helps to identify any gaps in protection, resolve any potential protection conflicts, and identify any single-point-failure conditions. All interrupt and operational constraint violations are subject to delay timing settings (see 4.5.3). Operational limit violations should only trigger a warning when it would provide information useful for control or maintenance operations. For example, the system should not issue a warning every time the module fans activate, while it is warranted to do so every time the ESMS limits power commands based on module temperature. A protection conflict can arise any time two devices are controlling the same value. The protection coordination design provides useful input to a failure modes and effects analysis (FMEA) [B12].

4. Hardware, software, devices, and functions

4.1 General

This clause provides information about battery management technologies including both hardware and software. The information provided here helps as a guide to the various design options and to the state of the technology. This information is referenced in 4.6 to recommend best practices for what designers should use for a given battery type in each energy storage application. Note that compliance with this document does not constitute compliance with applicable laws and regulations. Users are responsible for observing all local, state, regional, and national safety requirements for BMS hardware, software, devices, and functions.

4.2 Battery management devices and systems

4.2.1 General

Subclause 4.2 provides information on the hardware and software structures used in battery management.

4.2.2 Management systems external to the BMS

Although the BMS purpose is to maintain operational limits defined by the SOA, many operational limits are enforced by external management systems that may or may not interact with the BMS. Temperature management is one example of a battery management function that is commonly delegated to an external device or system such as a thermostat or HVAC unit. Gas management systems to prevent the buildup of hydrogen or other gases are another such example. An overall system design should enforce all operational and interrupt limits but various devices and systems external to the BMS may be used. Interrupt limits may be enforced using sensors internal to the BMS (as in the case with temperature) or through external sensing and the BMS emergency stop system (see 4.2.7).

4.2.3 Sensors

4.2.3.1 General

BMSs should be equipped with all sensors required to perform the battery management functions (see 4.5) recommended for a battery's application (see 5.2) and type (see 5.3).

Common sensor types include the following:

- Voltage sensors to perform voltage management functions (see 4.5.5)
- Current sensors to perform current and SOC management functions (see 4.5.6 and 4.5.8)
- Temperature sensors to perform temperature management functions (see 4.5.7)
- Pressure, flow, and level sensors to perform flow battery management functions (see 4.5.9)

4.2.3.2 Sensor accuracy

The required accuracy of sensing of various battery operating parameters depends on the sensitivity and variability of each parameter and its effect on safety and reliability. For example, for lithium-ion cells with nickel-based positive materials, with their sloping characteristic of voltage against SOC, an error of 10 mV in cell-voltage sensing represents an SOC-estimation error of only around 1%. In lithium iron phosphate (LFP)-based lithium-ion cells, however, flat spots in the open circuit voltage (OCV) curve have only a 1 mV change per 10% change in SOC, therefore, these cells could benefit from more accurate voltage sensors.

In applications requiring prolonged charge-discharge cycling at partial state of charge (PSOC), it is normal to use coulomb-counting to calculate SOC, in which the current flows in and out of each string are monitored over time. Depending on the accuracy of current sensing and state-of-health (SOH) assessment, SOC errors could accumulate over time. However, chemistries with sloping voltage characteristics offer an opportunity to correct the SOC whenever the battery has minimal current flow for several seconds. On the other hand, a chemistry with a flat voltage characteristic, such as lithium-ion cells with LFP positive material, does not offer the same opportunity. Consequently, LFP batteries would benefit from more accurate current sensing than would nickel-based batteries. Table 3 in 6.2.3 includes a list of recommended sensor accuracies. At present, precision resistance shunts are the most accurate method of measuring battery current, followed by Hall-Effect inductive current sensors, which measure current by sensing the strength of the magnetic field surrounding a wire. However, precision resistance shunts are often impractical in large, high-current battery systems due to cost and space constraints. Hall-Effect sensors are recommended as they provide sufficient accuracy at lower cost and with a smaller design footprint. Current transformer type sensors are designed to measure alternating current and do not work for measuring the direct current in battery systems.

Voltage, current, and/or temperature measurements may also be used to indicate possible safety-related conditions, such as thermal runaway in lithium-ion batteries. The alarm thresholds for such measurements typically include generous safety margins.

4.2.3.3 Redundancy of sensors and other hardware

Sensor redundancy may be required in some high reliability applications. A detailed FMEA [B12] or other hazard mitigation analysis is required to determine the necessity of redundant sensing and execution of safety functions. If, for example, it is determined that not knowing the correct cell voltages while charging might lead to catastrophic failure, then it could be necessary to provide redundant voltage sensing as an alternative to tripping the string upon sensor failure. However, if the cost of a single-string outage is low, then the added cost of redundant sensing would not be justified.

Hazard mitigation analysis can show whether accuracy of some battery data, such as temperature, is critical. For example, the difference between normal operation and temperatures that indicate a thermal-runaway failure can be significant, so that the accuracy of the temperature sensors does not have to be as high as that of a voltage sensor.

The need for other redundant hardware should be assessed relative to the impact of single-point failure on reliability and availability of the overall system.

4.2.4 BMS data aggregation

In multi-string battery architectures where each string has its own BMS, the status of each string is generally aggregated by a single device for communication to the system-level controller. It is recommended that designers employ a dynamic client-server relationship among the string-level BMSs, where one unit assumes the server function and fails over to another unit in the event of a problem. This approach can help reduce hardware and increase redundancy.

If the server BMS is a dedicated piece of hardware, it could represent a single point of failure, resulting in possible loss of all or a significant portion of the battery. The impact of such failures can be reduced by having two such devices with mirrored operation.

4.2.5 BMS power supply

4.2.5.1 General

The BMS needs to be powered according to its specifications. The BMS may be provided with its own auxiliary circuit that is fed from a separate auxiliary power supply, or it may be tapped off another auxiliary circuit. In some cases, the BMS is powered by the batteries themselves through an internal dc-dc converter, connected directly to the full battery voltage, and with the required output voltage (usually 24 Vdc). Powering the BMS solely from the battery being managed should not be done in battery systems subject to field servicing where there is mid-string circuit interruption or some other form of sectionalization.

4.2.5.2 BMS backup power

Requirements for BMS backup power duration vary. A BMS should have enough backup power to put the battery into a safer state after its primary source of power is interrupted. Additionally, certain authorities having jurisdiction (AHJs) require safety-critical fire and explosion protection systems to have at least 24 h of backup power. In standby applications, the BMS should be powered for at least the duration of the duty cycle and should be able to wake up later when external power is restored, and the battery can be recharged. This backup power can be accomplished in at least two ways: dedicated backup battery, or the battery itself through a dc-dc converter (see 4.2.5.1). The BMS backup power shall not draw power from a battery to reduce its voltage to an unsafe voltage or charge. If the managed battery is used as a backup supply, then the minimum state-of-energy during operation can be set based on the average power usage for the BMS and duration specification. For example, a BMS for a 60 kWh battery that draws 125 W during operation and needs 8 h of backup power can reserve 1.67% of its energy capacity so that the BMS can remain operational.

In standby applications, the BMS should be powered for at least the duration of the duty cycle and should be able to wake up later when external power is restored, and the battery can be recharged.

A dedicated BMS backup battery or uninterruptible power supply (UPS) can be sized based on the average power usage for the BMS and duration specification and should be oversized to account for its expected degradation during its service life. This reserve may be added to other operational reserves for a combined reserve.

4.2.6 Balancing circuits

Charge imbalance increases over time due to manufacturing differences between cells in a string. Batteries that are not able to be balanced through electrolysis or other means should be managed by a BMS that includes a balancing circuit (BC).

The design of the BC should balance efficiency with complexity, reliability, and cost. A BC design should minimize both the number and length of current carrying wires.

Balancing circuits use a range of architectures. Some examples are shown in Figure 5. The BC's architecture should match the physical architecture of the battery. In single-string balancing, wires run from a central BMS to the connection points between each cell in a string. Single-string balancing minimizes BMS complexity at the cost of very long wire runs. Single string balancing is not recommended for stationary batteries over 240 V. Module-based balancing only balances cells within modules, which generally has very short wire runs. This architecture also has lower insulation requirements between cell voltage measurement and balancing channels in the BC because it is not exposed to the full string's voltage. BMSs with a module-based balancing should be implemented with passive balancing and a common voltage tolerance band, either through identical settings or a communication channel, to prevent module imbalance. Tiered balancing is a combination of single-string and module-based balancing where balancing is performed within each module and then the modules are balanced within the string. Interleaved balancing, an architecture where BCs in a string overlap with each other, is used in some niche applications with requirements for BC redundancy.

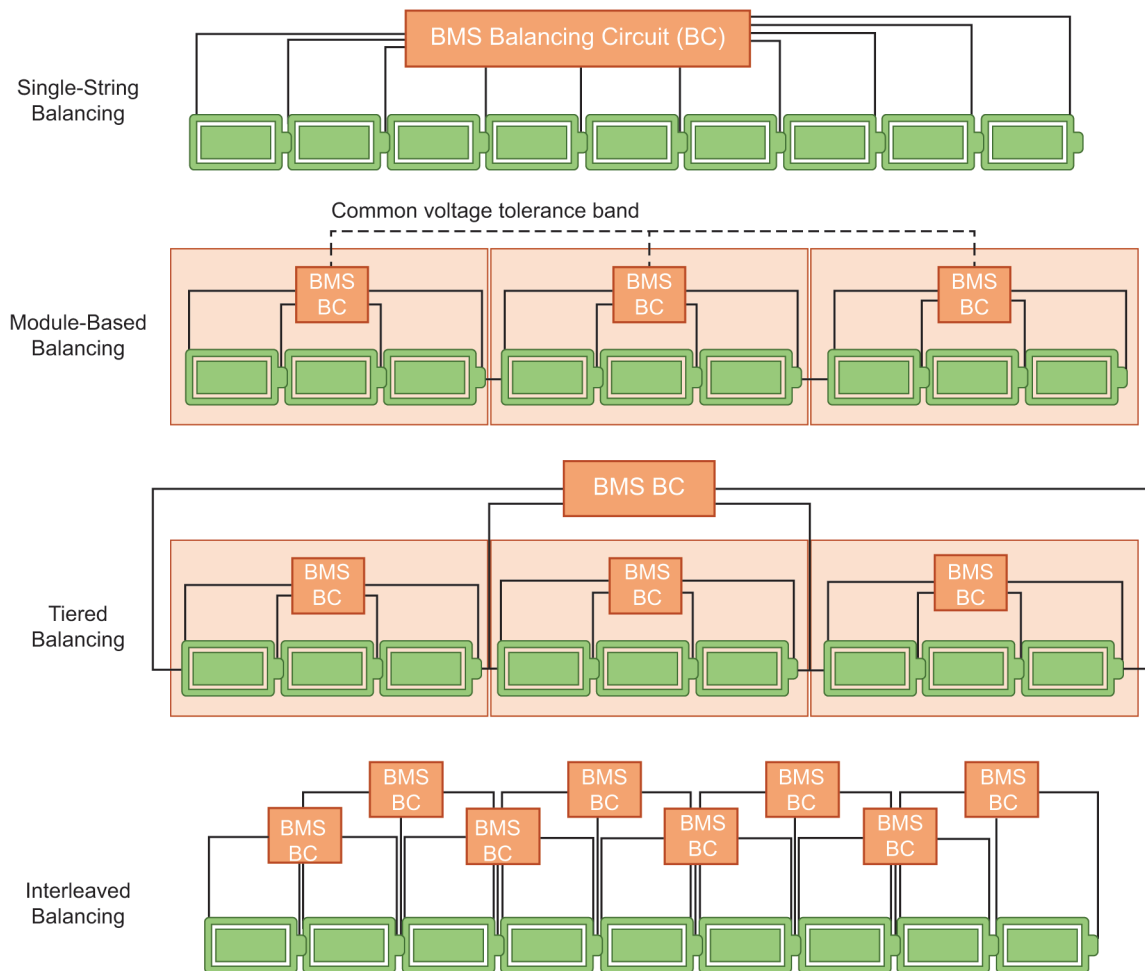


Figure 5—Example balancing circuit (BC) architectures

Some BCs have specific operation requirements, such as to operate only when the battery is at rest at a high SOC or low SOC for a specified amount of time. The BMS should be configured to warn the ESMS or operator when the BC's operational requirements are not being met. A multi-string BMS may be configured to take one or more strings out of service at a time to meet operation requirements for balancing.

A BMS BC should be rated by both its maximum balancing current, and its maximum sustained balancing power. For passive balancing using one shunt resistor for every cell, which is currently the most common form of BC, there is no limitation on the number of cells that can be balanced. Therefore, the circuit's balancing current should exceed the highest rate of cell self-discharge by a suitable margin. For active BCs, or circuits with fewer resistors than cells in series, additional calculations are required (see [Annex B](#)).

The circuit elements for a BC should be sized appropriately to keep a string of cells within a specified voltage tolerance window. The BMS total sustained balancing power should be sufficiently greater than the total energy imbalance rate to account for this increase. A factor of three or greater is recommended.

A BC should be designed to bring cells to within a range of SOC depending on the accuracy of voltage measurement. Voltage is used as a proxy for cell SOC, so the range may be measured in terms of a maximum voltage differential among resting cells. A wider voltage range allows the BC more and longer periods of inactivity, thereby reducing standby losses. A narrower range increases the usable capacity of the battery string but results in more frequent actuation of BCs. For passive balancing with shunt resistors, the typical voltage band is 30 mV.

4.2.7 Emergency stop system

The BMS should include a direct trip circuit, driven by dry contacts, through which external devices and systems can cause current-rated switches (see [4.2.8.3.1](#)) to open. This circuit should bypass normal BMS communication and should be resettable only by qualified personnel. Examples of external devices and systems that may operate the emergency stop include the following:

- The fire alarm system (see [4.2.8.5](#))
- Vent-gas detection systems (see [4.2.8.10](#))
- The ESMS
- PCS firmware (PCS failure)
- Manual emergency power-off-switch (big red button)
- Cabinet door contacts (detects when the doors are opened)

4.2.8 Peripheral devices and equipment

4.2.8.1 General

[Subclause 4.2.8](#) describes various devices and equipment that may be installed in or connected to a BMS. Some of these devices are not a part of the BMS but they do interact with the BMS and affect its operation.

4.2.8.2 Pre-charge circuits

The initial connection between a battery and PCS (see [4.6](#)), often done during commissioning or after an outage, can induce a significant inrush current to charge the PCS's internal capacitors. Significant inrush currents can cause welded contactors or other damage. In such cases, a pre-charge circuit is used to limit the magnitude of the current. A pre-charge circuit places a resistor in series with the battery while the battery is charging the PCS's capacitors, see [Figure 6](#). The resistor for a pre-charge circuit should be sized to limit the inrush current to within the interrupt constraints of the battery such that the BMS does not trip the battery during pre-charge. A parallel switch then closes to short-circuit the resistor so that it does not dissipate power during normal operation.

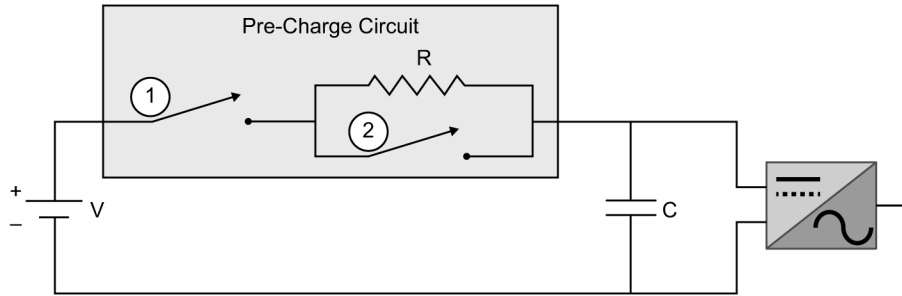


Figure 6—Pre-charge circuit, (1) first switch to close, (2) second switch to close

4.2.8.3 Circuit interrupting devices

4.2.8.3.1 Current-rated switches

The BMS should be able to interrupt the battery's operation by opening a circuit interrupting switch. This switch should be rated to interrupt the maximum operational current of the battery. Switch operation should be coordinated with the PCS and ESMS. Any single device should be able to open the switch, either internally if initiated by the BMS itself, by normal communication of a stop command, or through the emergency stop system (see 4.2.7). All devices should agree to close the switch, and the BMS should not close the switch unless the battery is within its SOA with no warnings or alarms.

Current-rated switches can fail closed. Examples include a welded contactor and shorted metal-oxide-semiconductor field-effect transistor (MOSFET). The BMS should be configured to verify switch operation periodically on an automated schedule, for example, by opening the switch during a period of low-current flow and verifying that current flow is stopped. Where possible, this action should be coordinated between strings so that current supply to the application is not disrupted.

MOSFET switches may be more appropriate for low-voltage applications like telecom because it takes less power to keep them closed. Power MOSFETs generally cost more than contactors with equivalent ratings; therefore, they are not common in applications where standby power is not a primary design consideration. They are also good in standby applications, having an intrinsic diode that allows the battery to be simultaneously blocked from charging and allowed to discharge. On the other hand, contactors are the normal choice for high-current, high-voltage applications where MOSFET heat dissipation should be assessed.

4.2.8.3.2 Non-current-rated switches

Non-current-rated switches are devices that can break a battery circuit but are not rated to interrupt the full operating current and may be used in the battery circuit. These devices are used to isolate or sectionalize battery modules for safety during maintenance or transportation. When a circuit breaker is used for short-circuit protection (see 4.2.8.3.3), its manual opening can provide the same functionality as a non-current-rated switch provided it has lockout/tagout capability. Alternatively, when fuses are used for short-circuit protection, and a stop command is used to interrupt operation for servicing activities (see 4.2.8.3.1), a manual non-current-rated disconnect is opened and locked to prevent unexpected energization.

WARNING

Manual non-current-rated switches should be clearly labeled as follows:

DO NOT OPEN WHILE BATTERY IS CHARGING OR DISCHARGING.

Safety disconnect switches are required to have lockout/tagout capability by many regional electrical safety regulations (OSHA 29 CFR [B45]). The BMS should not open these switches unless it first checks that the current passing through them is within their rating. The BMS should not close these switches unless the battery is in a safe condition.

4.2.8.3.3 Short-circuit protective devices

The BMS should include a protective device that opens autonomously in the event of a short-circuit. These devices include dc circuit breakers and fuses, and they should be sized to allow maximum operational current while quickly interrupting short-circuit current. The action of short-circuit protection is an important factor in the calculation of dc arc flash hazard (NFPA 70E [B43]). Many pack designers choose fuses over circuit breakers because of their speed advantage. Sometimes, a combination of controlled switch interruption with fuses offers complete protection that covers both extremely high short-circuit interruptions as well as moderate overload protection. Except for motor operated breakers, short-circuit protective devices need to be reclosed or replaced manually by a technician following a short-circuit.

The BMS current-rated switch (see 4.2.8.3.1) should be rated to withstand a short circuit for the time it takes for the short-circuit protective device to open the circuit. When three or more strings are placed in parallel, a special case should be considered where a short occurs on the battery side of the BMS's short-circuit protective device. In that case, current from the other strings can flow into the short circuit, possibly exceeding the interrupt rating of that BMS's short-circuit protective device.

When a fuse is used for short-circuit protection, the BMS should include a non-current-rated switch (see 4.2.8.3.2). When a circuit breaker is used, it should have lockout/tagout capability and a separate, non-current-rated switch is not recommended.

4.2.8.4 Ground fault identification circuit

Battery systems may be positively grounded, negatively grounded, grounded at a mid-string location, or ungrounded. Ungrounded battery systems can include a high impedance connection to ground, often located in the PCS, that prevents the buildup of static charge on the dc bus. Ungrounded batteries can be less prone to accidental short circuit as two inadvertent shorts to ground are required to achieve a complete circuit. Ungrounded batteries, or high impedance grounded batteries, can also reduce risk, because to receive a shock, a worker would typically need to contact two exposed conductors, rather than one conductor, and the enclosure or rack. The resistance to ground from exposed conductors should be greater than 25 Ω/V to limit short-circuit current through ground to below 40 mA. If there is a ground fault in one part of the battery circuit, then the voltage from exposed battery terminals in another part of the battery circuit to the grounded enclosure or rack could pose a burn or even arc flash hazard. Ground faults don't necessarily have to be hard shorts to earth or chassis ground. A ground fault in battery systems can result from many things, including the following:

- Damaged electrical insulation: cable jacket fatigue, heat, vibration, rodent, aging, corrosion, etc.
- Deficient installation: pinched cables, inadequate grounding
- Battery or filter capacitor electrolyte leakage
- Salt accumulation, condensation, and water infiltration
- Electrical equipment parasitic capacitors failure

Ground faults can lead to erratic equipment operation, protection device tripping, shocks, fire, and arc flash in high voltage application.

A BMS for an ungrounded or high impedance to ground battery should have a circuit to identify ground faults when they occur. As soon as a ground fault occurs, the risk of shock increases from someone touching just one conductor in the battery string and the battery enclosure. Ground fault identification circuits have threshold