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

STANDARDS

IEEE Power and Energy Society

Developed by the
Energy Storage and Stationary Battery Committee

IEEE Std 2686™-2024

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

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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Christopher Belcher
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Daniel Boyer
Raymond Byrne
Thomas Carpenter
Siu-yee Ching Vera
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Haissam Nasrat
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Benjamin Schenkman
Onur Usmen
Vilayanur Viswanathan
Rachel Wood

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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.

Contents

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.

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[6]The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.
[7]The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.
[8]IEEE publications are available from The Institute of Electrical and Electronics Engineers (https://standards.ieee.org/).
[9]The 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.
[11]Notes 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.

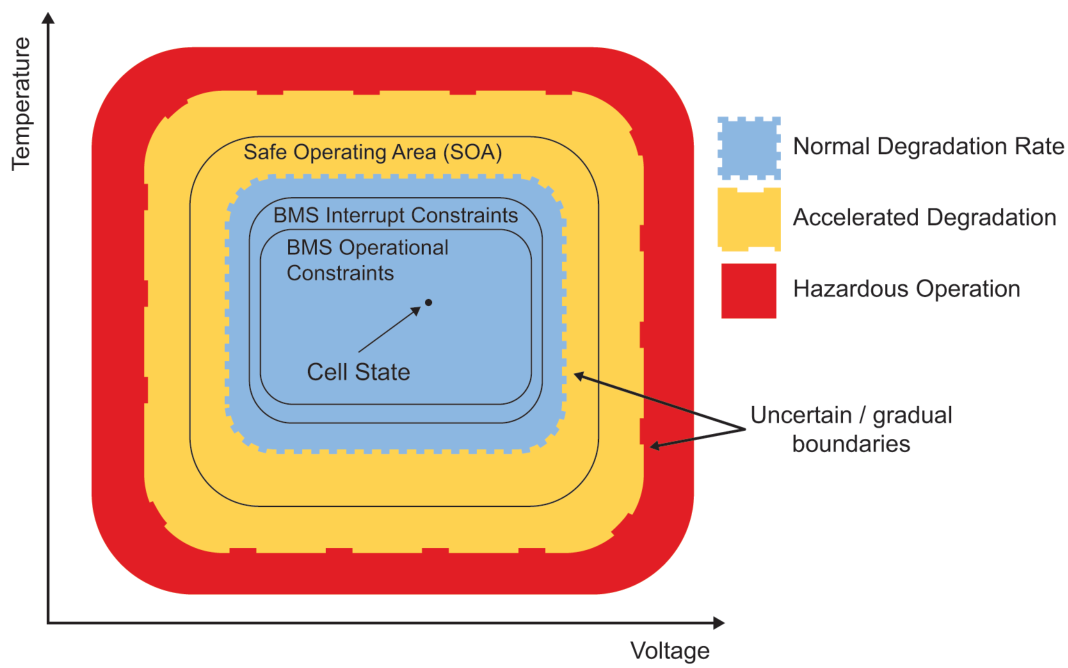

Figure 1—Example steady-state SOA enforced by a BMS

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 SOCs 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).

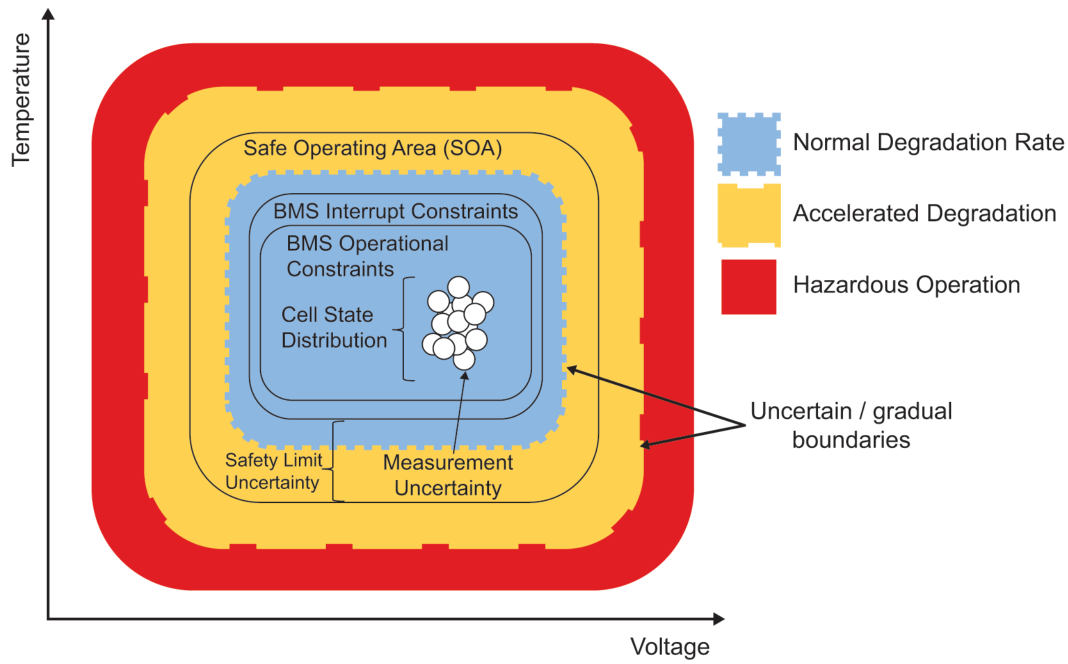

Figure 2—SOA of a string of cells or modules with variance and uncertainty

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 warrantee 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.

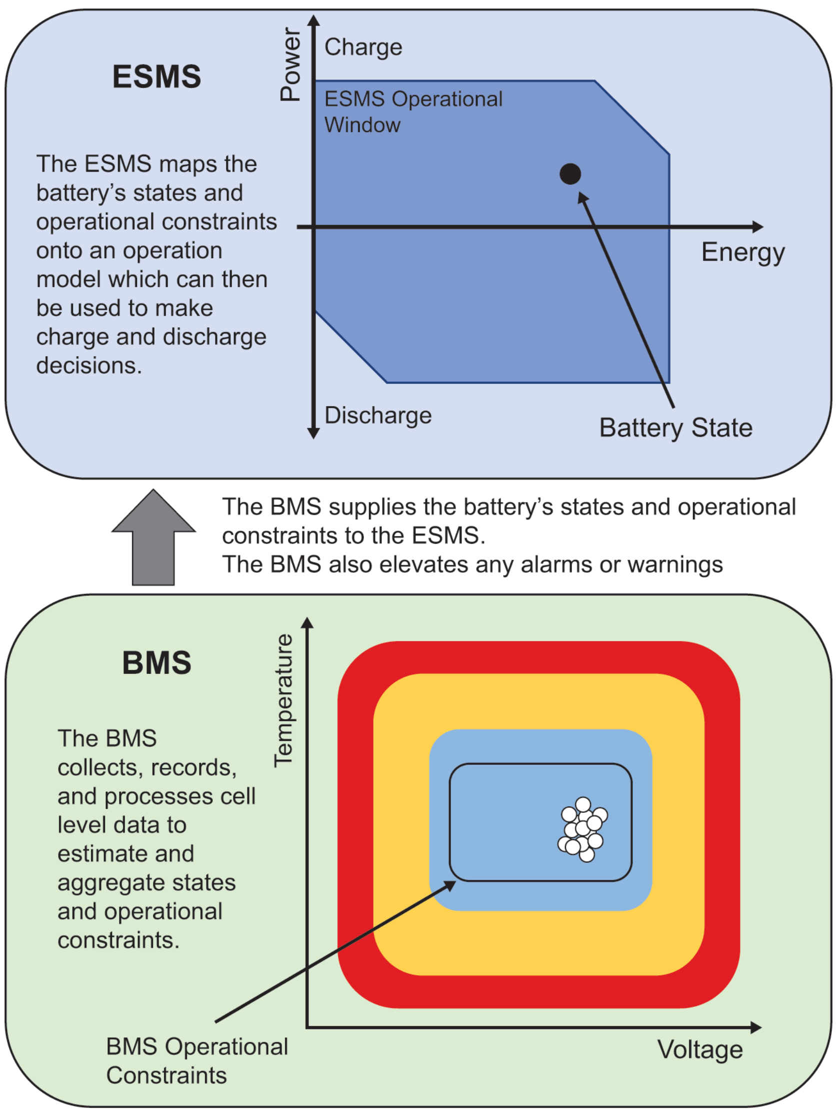

Figure 3—Illustration of BMS-ESMS interactions

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

[1]O# - operational constraint. This device has control of the managed value. The # indicates the order that the devices should act when controlling the managed value.
[2]I# - 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.
[c]management function implemented on each battery **cell** in the system.
[s]management function implemented on each battery **string** in the system.
[m]management function implemented on each battery **module** in the system.

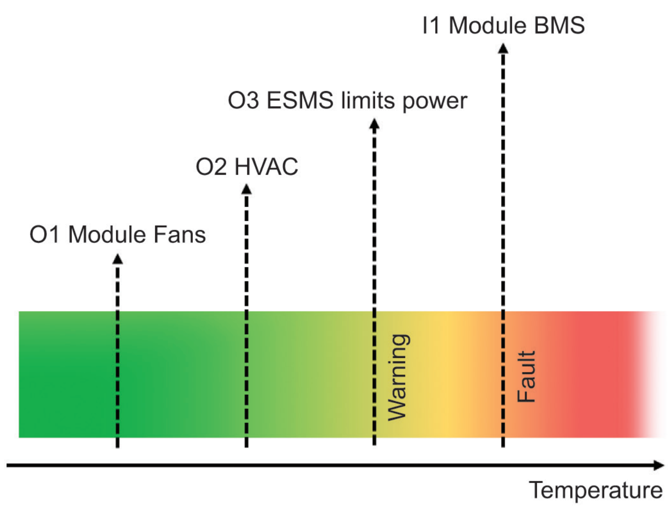

Figure 4—Illustration of example protection coordination for temperature management

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 back-up 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 though 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.

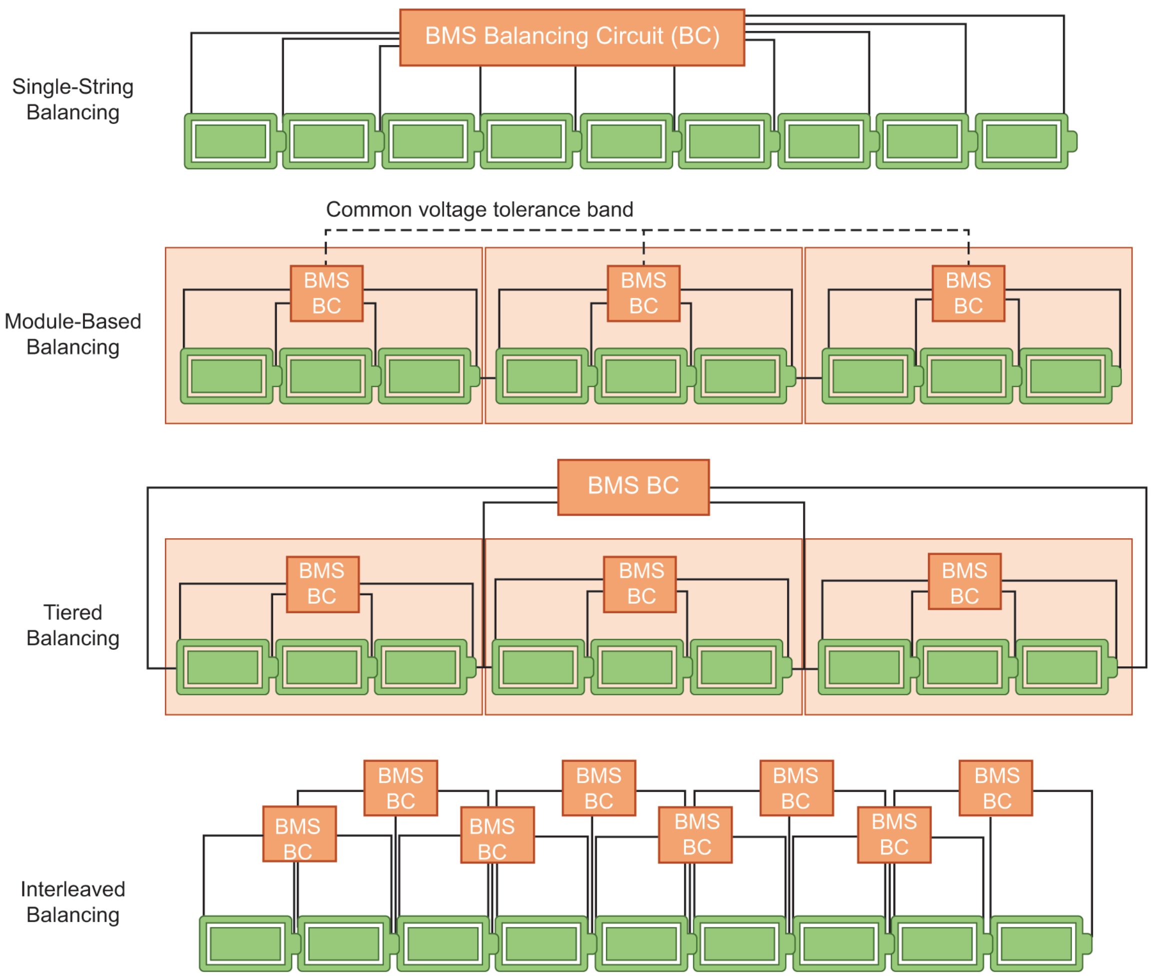

Figure 5—Example balancing circuit (BC) architectures

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.

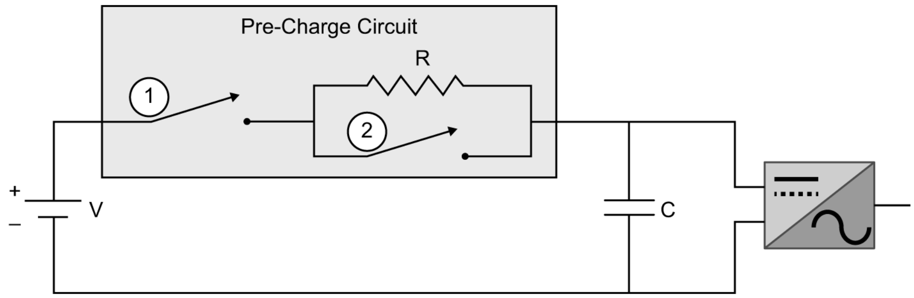

Figure 6—Pre-charge circuit, (1) first switch to close, (2) second switch to close

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 reading 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 settings to identify ground faults that develop gradually. These thresholds define operational and interrupt constraints so that warnings can be sent before system shutdown. The sensor # and timestamp for the warning should be available on the diagnostic bus (see 6.4).

Typical ground fault detection in high impedance and ungrounded systems include the following:

— Monitoring of the impedance (resistance) from the circuit to a bonded and grounded conductor. Typical resistance should be 1 MΩ or higher (typically 1 MΩ/1000 V with a minimum of 1 MΩ). Monitoring resistance is made by monitoring the voltage balance between conductors and ground through a high impedance resistor network. Any unbalancing voltage beyond required value can provide an indication of a ground leakage (reduced resistance to ground).
— Detection of the residual current: residual current detectors monitor the difference between the current flowing in the positive and the negative leads. A difference between the two currents can indicate a leakage to ground.

Only one ground fault identification circuit should be installed on a battery at any given time as the signal can interfere with other circuits and yield invalid or unreliable results. As inverters and chargers often include a ground fault identification circuit, installers should clearly identify if the BMS or the PCS have an active ground fault detector and which ground fault identification circuit is disconnected. Installers should follow the manufacturer's recommended procedure for disconnecting a ground fault circuit in a BMS.

4.2.8.5 Fire alarm system

The fire alarm system[12] controls the fire alarm and fire suppression system (FSS) in buildings, and these systems are also commonly found in BESS installed in buildings, containers, or enclosures. The fire alarm system typically is used to sense a fire, sound alarms, signal a remote first responding service, and trigger the FSS.

The fire alarm system switch should be wired to the BMS emergency stop circuit (see 4.2.7) to stop battery operation when a fire is detected. Some advanced battery management algorithms or sensors (see 4.2.8.10) may be able to identify early indicators of a thermal runaway event that could lead to a fire. In such cases, the BMS may be configured to notify the fire alarm system when a thermal runaway event is detected or predicted.

4.2.8.6 Liquid cooling system

Liquid cooling systems can be used for temperature management in battery systems. These systems include coolant loops or ducts, coolant reservoirs, fans, and/or pumps, motors, compressors, heat exchangers, and filters. The BMS may be configured to manage the operation of the pumps in the liquid cooling system. A liquid cooling system controlled by the BMS allows for more precise temperature management than the conventional HVAC unit controlled by a thermostat due to: 1) higher heat transfer rate of coolant, 2) BMS sensor location, and 3) near direct contact of coolant to the battery.

4.2.8.7 Fans

Module fans are commonly implemented in battery types whose degradation rate is sensitive to high temperatures. BMS activated and variable speed fans may be utilized to improve convective heat transfer within a battery system. Fans increase the parasitic losses of a battery system and should only be activated when needed. Fan operation should be based on average temperature, maximum temperature, minimum temperature, temperature differential, or some combination of these. Ideally, fan operation should be controlled at the level of individual modules and should be coordinated across all strings in an enclosure to reduce temperature differentials. If not managed correctly, electrical power used for the HVAC system can

[12]For information on fire protection in battery systems see NFPA 855 [B42], NFPA 1 [B37], NFPA 70 [B40], and the IFC [B30].

adversely affect the round-trip efficiency of the storage system. Variable temperature control and variable speed motors can reduce HVAC power usage and prolong its operating life.

4.2.8.8 Battery heaters

All batteries have an optimal temperature range in which they perform. When the ambient temperature is lower than that range and the internal losses of the cells are not enough to maintain their temperature above their lower limits, heaters controlled by the BMS may be employed to help maintain optimal temperature.

4.2.8.9 Hydrogen-gas detection

Any aqueous battery chemistry (with a water-based electrolyte) can generate hydrogen gas during regular cycling. However, aqueous battery chemistries generally do not use a BMS (see 5.3.5). The quantity of gas generation is dependent on many factors including the charging current, voltage, number of cells, and temperature. Rooms with batteries that generate hydrogen should be ventilated appropriately and monitored for hydrogen concentration. Guidance on calculating ventilation requirements for the most common aqueous battery types is provided in IEEE 1635™/ASHRAE 21 [B24]. Hydrogen's lower flammable limit (LFL) is around 4% concentration. The hydrogen concentration limit is set at 25% of LFL. The implementation of the calculated ventilation requirements restricts hydrogen buildup to less than 1%. If a buildup is detected, then an alarm should sound to warn people in the area and battery charging should stop. Hydrogen detectors can be wired to the BMS emergency stop circuit (see 4.2.7) to stop all battery operation.

4.2.8.10 Vent-gas detection

Vent-gas detection sensors or sensor networks can be installed in lithium-ion battery systems to detect trace amounts of vent gas chemicals that are released in the early stages of thermal runaway. If installed, this sensor should be configured to notify the fire alarm system (see 4.2.8.5) and trigger the emergency stop system (see 4.2.7) of all BMSs in the enclosure.

Li-ion batteries generate flammable and explosive gas when undergoing thermal runaway failure. This gas is not generated during normal operation, but can be produced in significant quantities during a cascading battery failure that reaches many cells/modules. The quantity of gas generation is dependent on many factors including the specific type of Li-ion battery, the amp-hour rating of the cells, the SOC and temperature of the cells, and the number of cells venting. Guidance on calculating ventilation requirements for some common lithium-ion battery types is provided in IEEE Std 1635™-2021/ASHRAE [B24]. The LFL for the gas depends on many factors but, as gas is generated quickly under failure conditions, it is best practice to trigger BMS actions on the presence of vent-gasses rather than a concentration threshold. Research on energy management strategies to reduce the likelihood of thermal runaway propagation in the time just after detection is ongoing (Mueller, J.A., et al. [B38]. More information on deflagration venting can be found in NFPA 855 [B44], and NFPA 68 [B40], and more information on explosion prevention systems can be found in NFPA 69 [B41].

4.3 Physical architecture

4.3.1 General

BMSs are structured in a variety of ways. Figure 7 shows a range of example physical architectures for battery management within modules and systems. Note that the terminology is context-dependent, so modules can have a "centralized" BMS within a "modular" system architecture. The physical architecture of the BMS should follow the physical architecture of the battery it serves. This means that the data collection, decision making, cell balancing (see 4.2.6), and protection actions of a BMS should operate on cells within any architectural units that are physically separated from other units. Therefore, if the battery is divided into modules, the BMS should also be divided to collect and act on data within those modules. A protection zone encompasses all batteries, strings, modules, and cells within the area the device controls. The electrical circuit that the BMS can interrupt is referred to as its electrical protection zone. When protection zones overlap, it is important to identify the order that the BMSs are to interrupt (see 3.5.2).

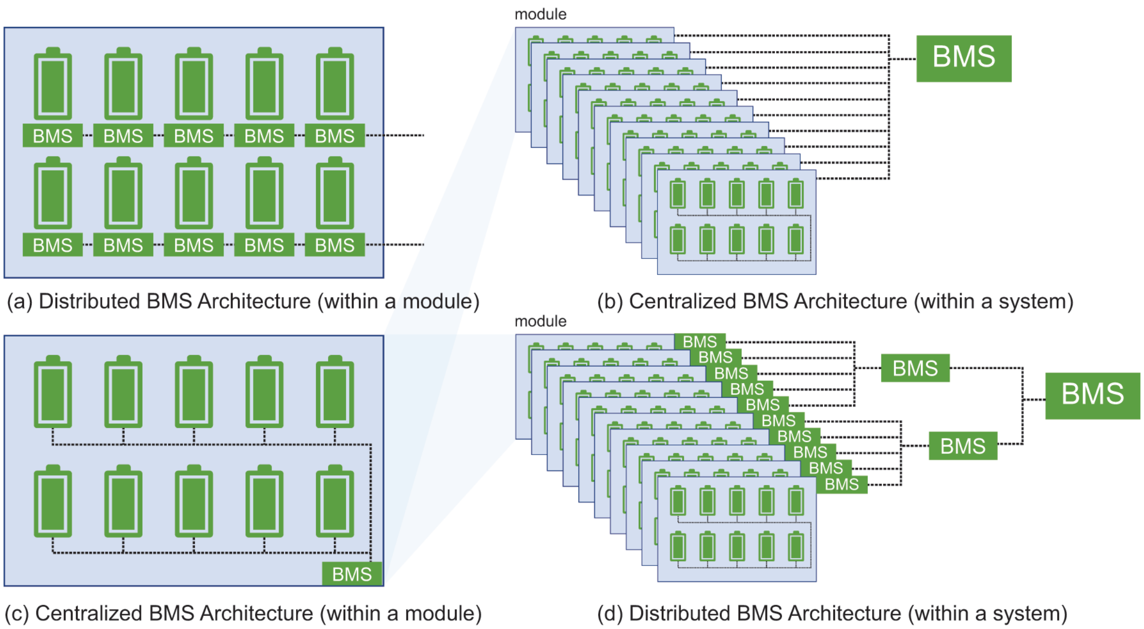

Figure 7—Different physical architectures for battery management

The BMS itself has several functional hardware elements, shown in Figure 8, that act together to protect the battery. The voltage sense leads are connected between each cell or group of parallel-connected cells in series, often on the positive terminal. The temperature sensors are distributed within the battery. The string's current can be measured through a current shunt or a hall-effect sensor (see 4.2.3.1). The data acquisition circuit then samples each measurement and converts it to a digital format. The voltage sense wires may be used by the cell BC to add or remove charge; however, this current could affect the measured voltage. Using shorter, higher gage BC wires can help reduce this effect, while many BMS circuits may be able to substantially eliminate the effect by using separate wires for balancing current and for voltage sensing. The battery measurements are then supplied to the battery management logic, running on a processor or microcontroller, which processes the data

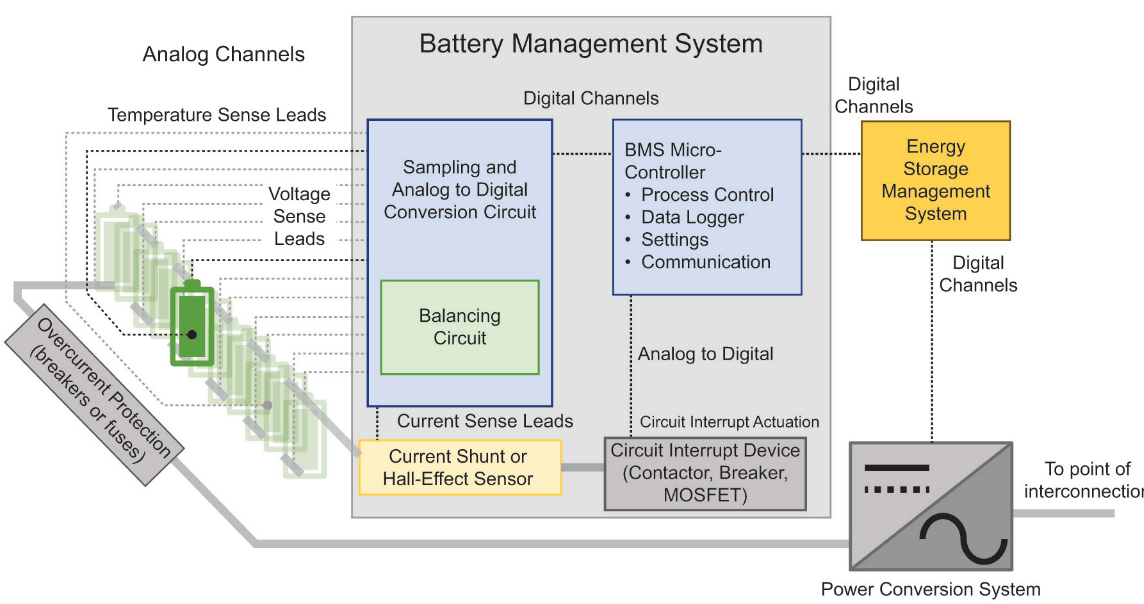

Figure 8—Battery management functional block diagram

and makes protection decisions. Interrupt constraints are enforced by the BMS actuating the circuit interrupt device (see 4.2.8.3). The BMS also calculates the limits that should be applied to the battery's operation and sends that to any upstream controller, such as an ESMS. For example, if the battery's temperature is cold, it might calculate a lower charging current than otherwise allowed and send that new limit to the ESMS.

4.3.2 Temperature sensor density

As it is often impractical to place a temperature sensor on each cell within a battery, a smaller number of them may be placed in strategic locations in the module.. The spacing of these sensors should be sufficiently dense to identify temperature gradients within the battery that could impact operational life. A greater number of temperature sensors enables finer resolution of temperature gradients within a module or string and, hence, more reliable identification of off normal conditions. Temperature gradients and, hence, sensor density is impacted by airflow, heat sinks, cell size and shape, liquid cooling, and many other physical factors. Redundant sensors, or a higher sensor density than is strictly needed for safety, enables higher reliability temperature management. If temperature sensors in battery modules are placed such that the loss of any one sensor does not lead to a condition where a high temperature gradient would go unidentified, then a single temperature sensor error may have a temperature management function output of a warning rather than a fault.

Temperature sensors should be placed to closely estimate internal cell temperature. In many battery types, the best placement location is on the negative terminal of the cell due to the high thermal conductivity of common negative electrode materials.

4.3.3 Managing parallel battery strings

When multiple battery strings are connected in parallel, the BMSs for each string should be coordinated (see 4.2.4). The coordination depends on the type of application. See 5.2.2.1 and 5.2.3.1 for information regarding multi-string batteries in grid supporting and non-grid supporting applications, respectively.

4.4 Software architecture

4.4.1 General

The BMS software architecture is divided into the following layers:

- Local inputs/outputs: acquisition of directly measured parameters such as temperature, current, and voltage that are directly inputted into the BMS. The data may be used as is or aggregated depending on BMS physical architecture (5.2.2).
- Real-time control computation stack:
  - Calculated parameters: values calculated from local inputs that are used in monitoring, protection, and control, such as battery SOC, battery SOH, or rate of change of measured parameters. These range from simple calculations or sophisticated empirical models.
  - Battery management functions: provides for protection, active management of cell and strings, and associated local controls, depending on the system architecture. It includes the functions of any subsystem or device (e.g., fire protection system, thermal management system) designed to support proper function, health, and longevity of the battery.
- Data aggregation and communication: the primary BMS (see 4.2.4) aggregates data in a multi-string battery system and communicates summary data to the ESMS.

Figure 9 provides an overview of the different layers and where these functions may reside within the BMS hardware. Actual software architecture varies depending on battery technology, system size, regulation requirements, and cost considerations.

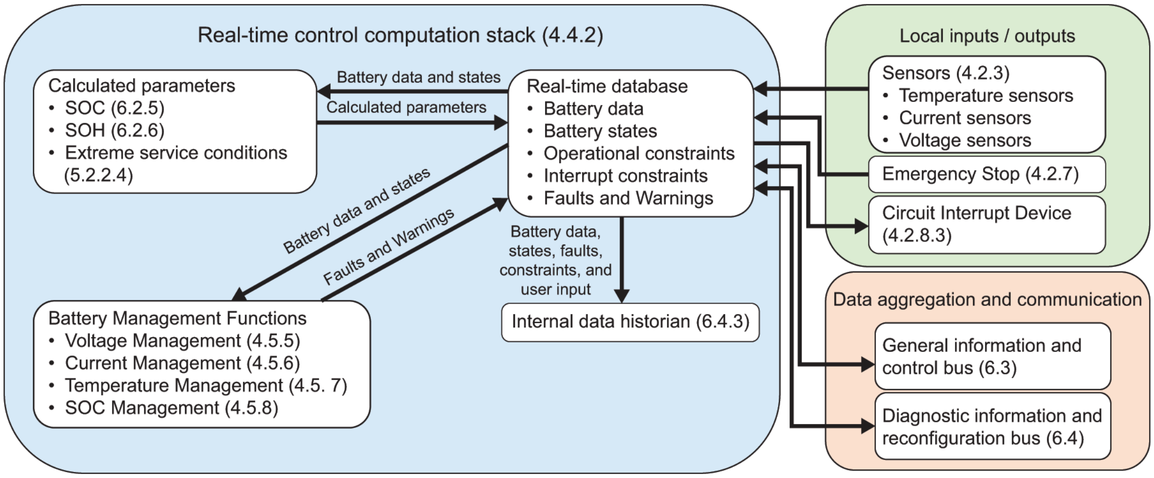

Figure 9—Software architecture layers for battery management

Having a dedicated ESMS provides benefits to larger systems that require better management of large data traffic and more sophisticated controls that may employ multiple use cases and interface with many stakeholders. The SunSpec Model Reference [B50] should be implemented to standardize communication between the BMS and other devices (see 6.3.1) and to provide for compatibility among different vendors. As standards get updated, it is important the latest major revisions of the standards are used to help reduce compatibility issues.

4.4.2 Real-time control computation stack

There are several timing clocks on which a BMS operates as illustrated in Figure 10. The fastest clock is normally the data acquisition clock which commonly operates between 10 Hz and 1000 Hz. Those data are then processed through a digital filter and supplied to the battery management clock. The battery management

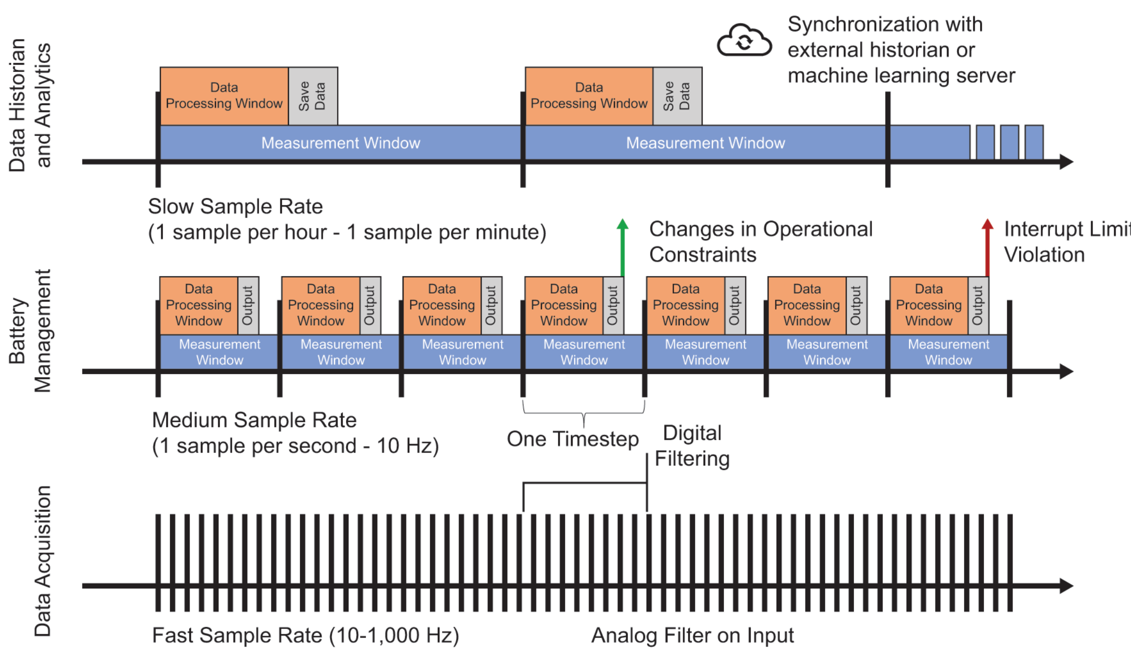

Figure 10—Hierarchy of aquation, management, and historian data rates

clock, commonly running in the 1 Hz to 10 Hz range, is the timing on which the BMS makes and implements protection actions. Note that some protection actions are activated directly from the data acquisition clock. Lastly, the data historian collects and records operational data for archival and analysis purposes. The historian clock normally operates in the 1 sample per minute to 1 sample per hour range. Sublause 6.2.4 provides recommendations on sample rate for on-board data storage.

4.4.3 Time synchronization

BMSs with an on-board clock should be able to synchronize the clock with an external device or the network clock regularly. Between synchronization events, the BMS should estimate time elapsed.

4.4.4 Local/remote control

The general control bus discussed in 6.3 enables operational or configuration changes to be made over a network connection. If the network that the general control bus is connected to is accessible from an offsite location, the system design should consider whether remote control could lead to any potential hazards for on-site personnel.

On-site personnel should be able to prevent remote changes to the BMS's operation and configuration by placing the battery in local control mode. The BMS should include an option in the software to place the battery in local or remote-control modes. In local-control mode, the BMS should not accept configuration changes that are made remotely (e.g., from the ESMS). In remote-control mode, the BMS should accept configuration changes that are made either locally or remotely.

4.4.5 Reset

Performing a reset should restore the BMS to its default settings. Resetting the device may restore the BMS to a previous, even factory installed, version of firmware. A BMS reset should be performed only by a technician with appropriate access (see 6.5.3.3).

4.4.6 Heartbeat

The BMS should include a heartbeat signal to enable a server BMS (see 4.2.4) and ESMS to identify when communication has been lost, the BMS has lost power, or the BMS has experienced an internal error. The heartbeat should increment an integer value once per second according to the battery management clock (see 4.4.2), and roll-over to zero periodically.

4.5 Battery management functions

4.5.1 General

Subclause 4.5.4 through 4.5.9 provide descriptions of several battery management functions. BMS functions support battery safety, longevity, or both through automated logic. There are two types of thresholds that BMS logic acts on: interrupt constraints and warning thresholds. Operational constraints may be calculated by the BMS but are generally implemented by other devices (e.g., the PCS). Within a BESS, operational and interrupt constraints should be coordinated for effective protection (see 3.5.2). Warnings are used by maintenance programs to identify when actions by personnel could help avoid future problems, such as outages or cell failures. Each function consists of an objective, description, inputs, settings, and outputs, as follows:

- *Objective*: the goal that the function aims to achieve
- *Description*: a description of how the function achieves the objective
- *Inputs*: the measured and calculated values that feed into the function
- *Settings*: operational and interrupt constraint thresholds including timing parameters
- *Outputs*: the enumerated possible outputs of the function

4.5.2 Function outputs

This subclause provides a description of the types of battery management function outputs. Some of these data are made available over the general information bus (see 6.3) while more details are made available over the diagnostic information bus (see 6.4). Outputs are as follows:

- *Normal Operation*: This output reflects that all battery states are within their operational limits.
- *Warning*: This is the output given if one or more of the battery's states has violated a warning threshold. Warning thresholds should be configured to identify aberrant operation that could lead to life-cycle or safety problems if left unadressed.
- *Fault*: This is the output given when one or more of the battery's interrupt constraints have been violated.
- *Error*: This output reflects that the BMS or one of its sensors have failed and some or all of the battery's current states are unknown.

4.5.3 Function action delay

To reduce occurrences of nuisance errors, warnings, and faults battery management functions should be configured with delay timing settings. A momentary loss of data from a sensor should not pose a hazard to the battery. The BMS should be configured such that a momentary loss of data from a sensor does not trigger an interrupt constraint. An extended loss of data from a sensor could lead to an unidentified violation of an interrupt constraint and might result in a hazardous condition. The distinction between momentary and extended loss of data is different for different battery management functions. Action delay is commonly implemented by a sequential AND gate filter (shown in Figure 11 where the limit needs to stay in an error, warning, or fault state for all samples in a specified period to trigger action. The varying values for delay timing are represented in Figure 12, Figure 13, Figure 14, Figure 15, and Figure 16 as $t_{function}$ where function is one of the following: warning high (WH), warning low (WL), fault high (FH), fault low (FL), or error (ER).

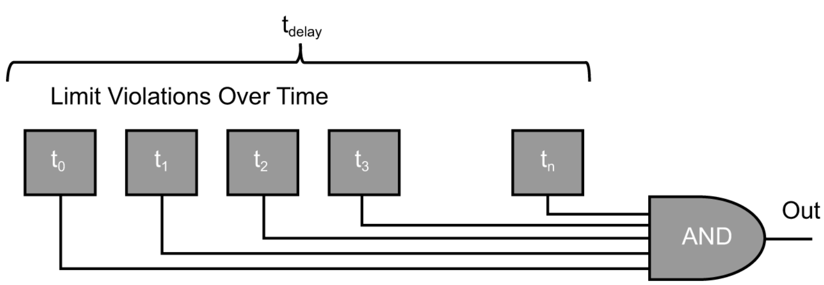

Figure 11—AND Gate Logical Filter for BMS Function Action Delay

It is also good practice to implement a minimum reset time for identical errors, warnings, and faults. A sensor fault can sometimes take days or weeks to fix, and logging a unique error each time a new measurement fails could be redundant and costly in terms of internal memory. Instead, identical errors, warnings, or fault messages may, unless otherwise cleared, be recorded once per day.

4.5.4 Fault reset

Functions should be configured with appropriate reset options. Available options should include the following:

- Automatic reset, e.g., a battery low-voltage fault at the end of discharge should be reset as soon as the battery is charged.

— Remote reset by operator, e.g., a high-temperature fault could be reset after an investigation of possible causes and verification of correct operation of the thermal management system.

— Local reset by technician, e.g., following replacement of a cell with a critical-low-voltage fault.

4.5.5 Voltage management

4.5.5.1 General

Voltage management is a combination of overvoltage and undervoltage protection. Figure 12 shows an example process diagram for voltage management.

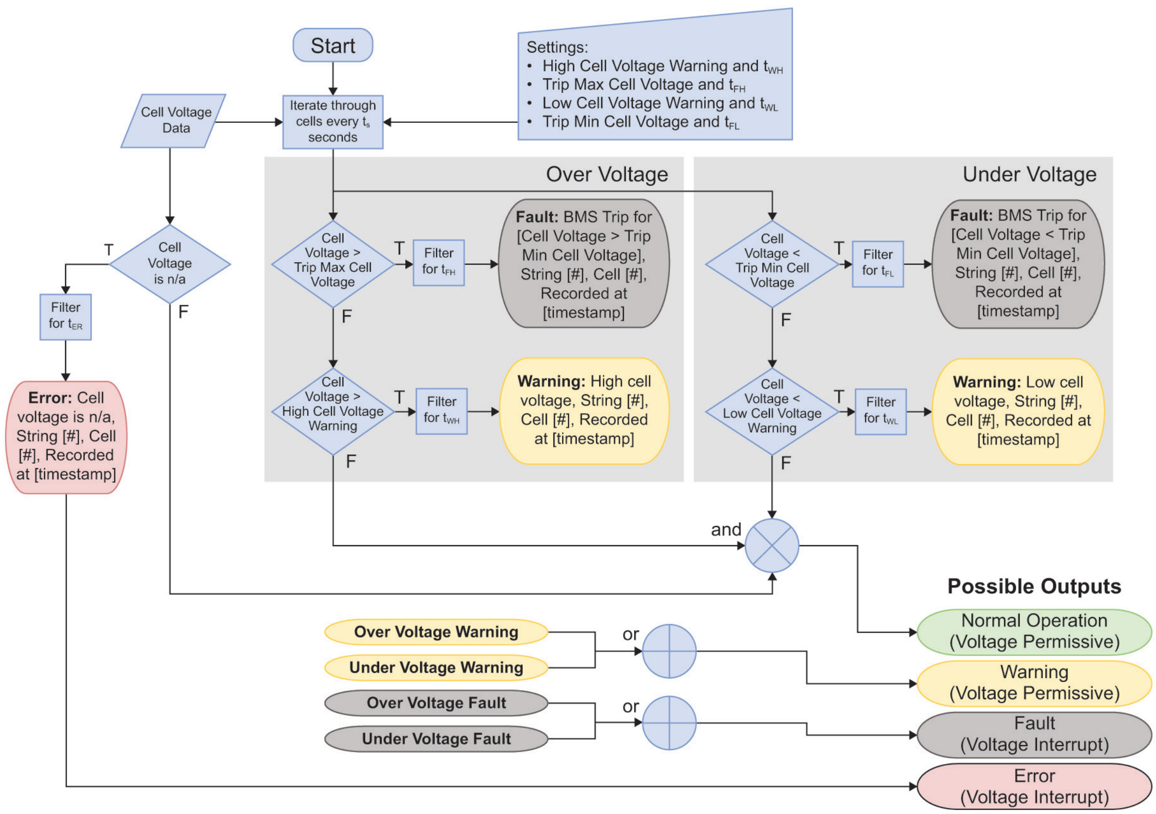

Figure 12—Example voltage-management process flow diagram

4.5.5.2 Overvoltage

— *Objective*: To prevent excessively high voltage from being applied to battery cells.

— *Description*: The operating upper voltage limits may be dynamic, changing as a function of temperature, SOC, or other operational states (e.g., if the string is undergoing a boost charge) as determined by the manufacturer. If a voltage at cell level/module level is measured to be greater than the maximum safe operating voltage limit, then this function triggers a Fault output. The setpoints for warning and trip max voltage should be coordinated with the inverter, which has a maximum dc voltage operating point. Designers should identify in which order the BMS and the inverter should limit charge current and trip.

— *Inputs*: cell voltages

— *Settings*: high cell voltage warning, trip max cell voltage
— *Outputs*:
  — Normal Operation (voltage permissive) flag (true/false)
  — Error: Cell voltage is n/a, String [#], Cell [#], Recorded at [timestamp]
  — Warning: BMS Warning for: Cell Voltage [V] > High Cell Voltage Warning [V], String [#], Cell [#], Recorded at [timestamp]
  — Fault: BMS Trip for: Cell Voltage [V] > Trip Max Cell Voltage [V], String [#], Cell [#], Recorded at [timestamp]

4.5.5.3 Undervoltage

— *Objective*: To prevent cells from reaching an excessively low voltage.
— *Description*: The operating lower voltage limits may be dynamic, changing as a function of temperature, SOC, or other operational states (e.g., if the BESS is supporting a critical load through a power outage) as determined by the manufacturer. If a voltage at cell level/module level is measured to be lower than the minimum safe operating voltage limit, then this function results in a Fault output. The setpoints for warning and trip min voltage should be coordinated with the inverter, which has a minimum dc voltage operating point. Additionally, the BMS may be configured with a warning threshold and interrupt constraint on low string voltage to prevent accelerated degradation at low voltage (see 5.3.2).
— *Inputs*: cell voltages
— *Settings*: low cell voltage warning, trip min cell voltage
— *Outputs*:
  — Normal Operation (voltage permissive) flag (true/false)
  — Error: Cell voltage is n/a, String [#], Cell [#], Recorded at [timestamp]
  — Warning: BMS Warning for: Cell Voltage [V] < Low Cell Voltage Warning [V], String [#], Cell [#], Recorded at [timestamp]
  — Fault: BMS Trip for: Cell Voltage [V] < Trip Min Cell Voltage [V], String [#], Cell [#], Recorded at [timestamp]

4.5.5.4 Voltage imbalance

— *Objective*: To identify failing or failed cells for replacement or refurbishment.
— *Description*: A voltage imbalance can occur if a cell exhibits self-discharge at a rate that is higher than the capability of BCs to correct, or if a BC has failed. Voltage imbalance is not a safety issue but could lead to lower or rapidly degrading string performance if the cell or module is not replaced.
— *Inputs*: cell voltages
— *Settings*: cell voltage imbalance warning
— *Outputs*:
  — Normal Operation (voltage permissive) flag (true/false)
  — Warning: BMS Warning for: High Voltage Imbalance [V] > Cell Voltage Imbalance Warning [V], String [#], Recorded at [timestamp]

4.5.6 Current management

4.5.6.1 General

Current management is to protect from excessive current both on charge and on discharge. Figure 13 shows an example process diagram for current management.

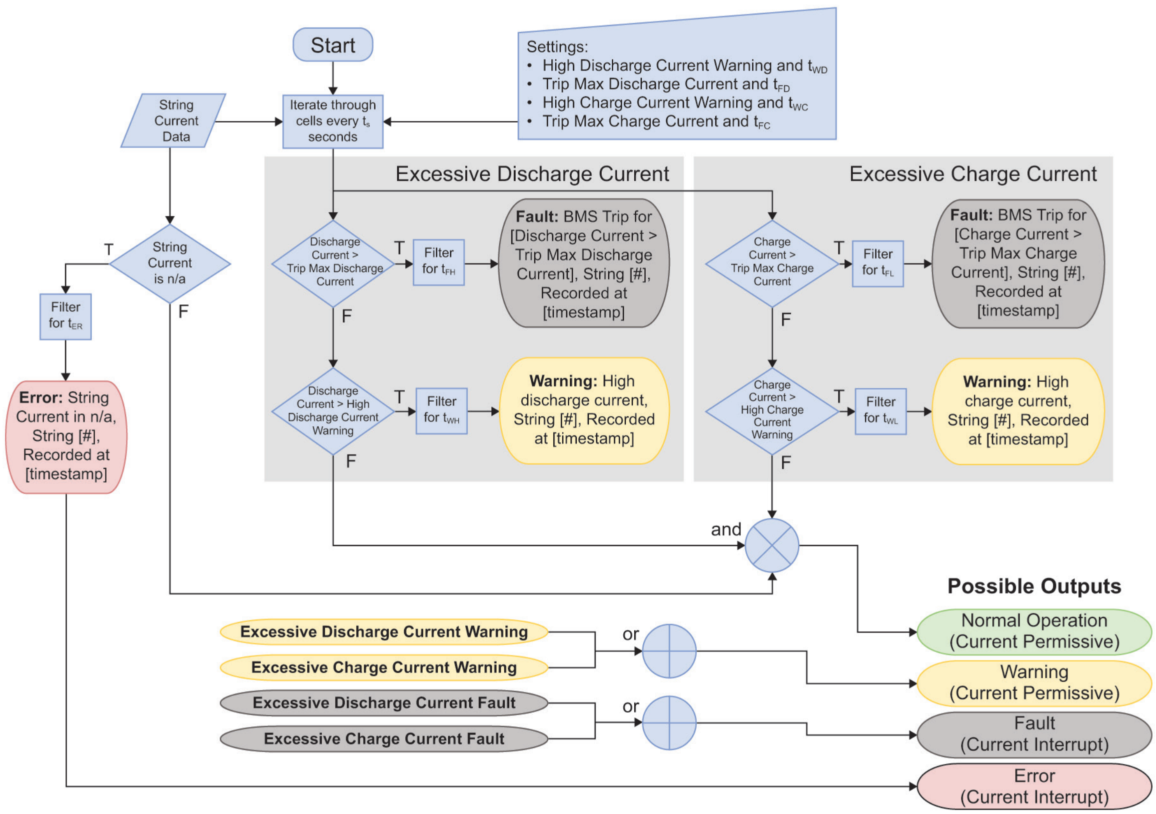

Figure 13—Example current management process flow diagram

4.5.6.2 Overcurrent

— *Objective*: To prevent excessive cell charge or discharge currents.

— *Description*: The BMS communicates the safe operating current range to the inverter/charger such that it can enforce operating constraints on current. The operating current limit may be dynamic, changing as a function of temperature, voltage, SOC, or other operational states as determined by the manufacturer. If the measured current of the string is greater than the maximum safe operating current limit, then the string is electrically isolated by sending a trip command to the circuit interrupt device.

— *Inputs*: string current data

— *Settings*: high discharge current warning, trip max discharge current, high charge current warning, trip max charge current

— *Outputs*:

  — Normal Operation (current permissive) flag (true/false)

  — Error: string current is n/a, String [#], Recorded at [timestamp]

— Warning: BMS Warning for: Discharge Current [I] > High Discharge Current Warning [I], String [#], Recorded at [timestamp]

— Warning: BMS Warning for: Charge Current [I] > High Charge Current Warning [I], String [#], Recorded at [timestamp]

— Fault: BMS Trip for Discharge Current [I] > Trip Max Discharge Current [I], String [#], Recorded at [timestamp]

— Fault: BMS Trip for Charge Current [I] > Trip Max Charge Current [I], String [#], Recorded at [timestamp]

4.5.7 Temperature management

4.5.7.1 General

Temperature management is to protect cells from excessively high or low temperatures. Figure 14 shows an example process diagram for temperature management.

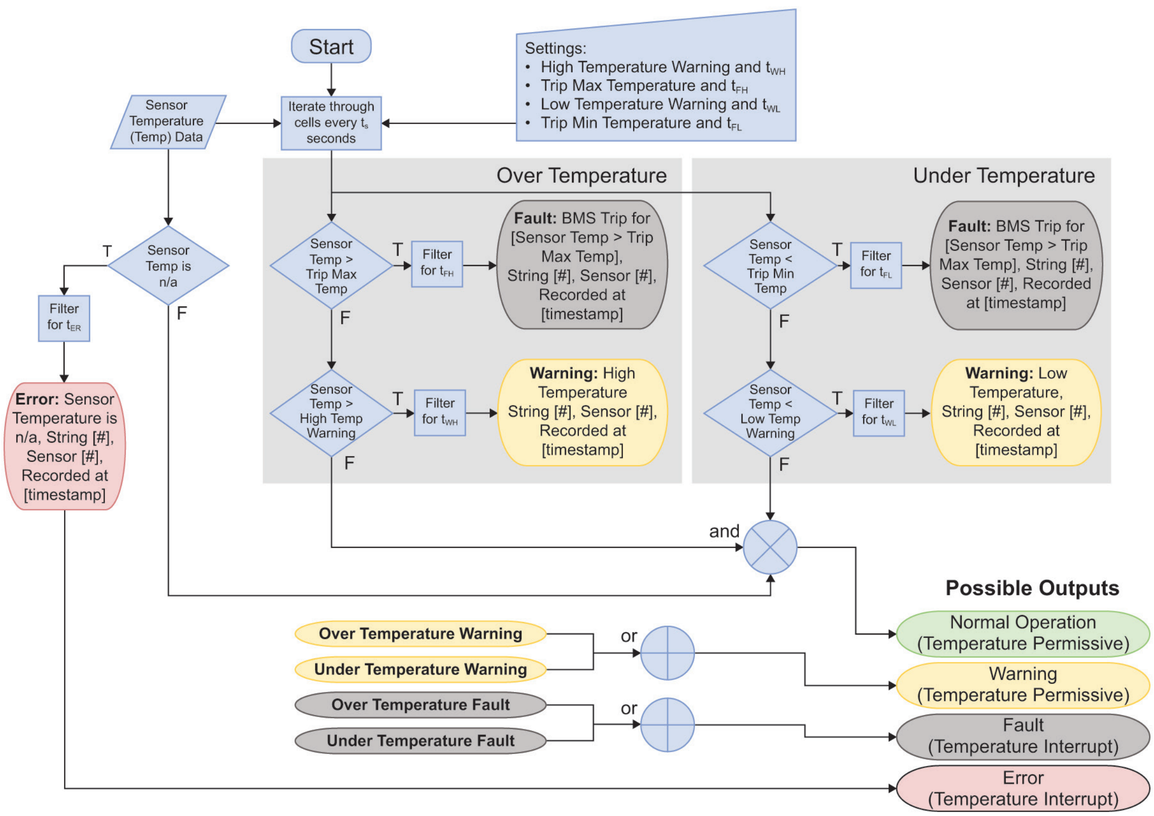

Figure 14—Example temperature-management process flow diagram

4.5.7.2 Overtemperature

- *Objective*: To prevent battery cells from operating under excessively high temperatures.
- *Description*: Operating a battery above a maximum temperature based on battery type can accelerate performance degradation and, in extreme cases, lead to early failure or a possible safety hazard. To help prevent this, the BMS should provide warnings when temperatures could lead to accelerated degradation and should fault when charge or discharge could lead to a safety hazard. The BMS may be configured to actively cool the batteries through liquid cooling systems, fans, or both (see 4.2.8.6 and 4.2.8.7). Active cooling may be triggered at a temperature threshold below the maximum operational temperature. Charge and discharge power/current limits may be reduced at high temperature and interrupts may be implemented based on current, rather than temperature. The operating temperature limits may be dynamic, changing as a function of SOC, or operational states as determined by the manufacturer. If the measured cell or module temperature is greater than the maximum safe operating temperature limit, then the string should be electrically isolated by sending a trip command to the circuit interrupt device.
- *Inputs*: Temperature measurements
- *Settings*: high temperature warning, trip max temperature
- *Outputs*:
  - Normal Operation (temperature permissive) flag (true/false)
  - Error: Temperature is n/a, String [#], Sensor [#], Recorded at [timestamp]
  - Warning: BMS Warning for: Sensor Temp [T] > High Temp Warning [T], String [#], Sensor [#], Recorded at [timestamp]
  - Fault: BMS Trip for: Sensor Temp [T] > Trip Max Temp [T], String [#], Sensor [#], Recorded at [timestamp]

4.5.7.3 Undertemperature

- *Objective*: To prevent battery cells from operating under excessively low temperatures.
- *Description*: Operating a battery below a minimum temperature based on battery type can result in accelerated performance degradation and possible failure. To help prevent this, the BMS should provide warnings when temperatures could lead to accelerated degradation and should fault when charge or discharge could lead to a safety hazard. The BMS may be configured to warm the batteries using battery heaters, see 4.2.8.7. Active heating may be triggered at a temperature threshold above the minimum operational temperature. The operating temperature limits may be dynamic, changing as a function of SOC or operational states as determined by the manufacturer. If the measured cell or module temperature is lower than the minimum safe operating temperature limit, the string should be electrically isolated by sending a trip command to the circuit interrupt device. Charge and discharge power/current limits may be reduced at low temperature and interrupts may be implemented based on current, rather than temperature.
- *Inputs*: Temperature data
- *Settings*: low temperature warning, trip min temperature
- *Outputs*:
  - Normal Operation (temperature permissive) flag (true/false)
  - Error: Temperature is n/a, String [#], Sensor [#], Recorded at [timestamp]

  - Warning: BMS Warning for: Sensor Temp [T] < Low Temp Warning [T], String [#], Sensor [#], Recorded at [timestamp]
  - Fault: BMS Trip for: Sensor Temp [T] < Trip Min Temp [T], String [#], Sensor [#], Recorded at [timestamp]

4.5.7.4 Temperature imbalance

- *Objective*: To identify problems in the heating/cooling system or possibly to identify failing or failed cells.
- *Description*: Heating and cooling systems are designed to keep a battery system within a nominal temperature range. However, blockages, obstructions, damaged equipment, and many other factors can cause a heating/cooling system to perform poorly. Problems often first present as increasing imbalances in temperature, rather than limit violations. This is might not be a safety issue per se but could lead to uneven or accelerated performance degradation and, therefore, should be addressed through maintenance.
- *Inputs*: Temperature data
- *Settings*: temperature imbalance warning
- *Outputs*:
  - Normal Operation (temperature permissive) flag (true/false)
  - Warning: Temperature Imbalance [T] > Temperature Imbalance Warning [T], String [#], Cell [#], Recorded at [timestamp]

4.5.8 SOC management

4.5.8.1 General

Most SOC management is performed by the ESMS through operational constraints. This subclause discusses functions for how the BMS can act to protect the battery in the case where the ESMS operational constraints are ineffective. SOC management is a combination of overcharge and overdischarge protection. Figure 15 shows an example process diagram for charge management.

NOTE—SOC management is applied to whatever unit of a battery system has an estimated SOC. If SOC is estimated for each cell, then SOC management is applied based on the highest or lowest value of individual cells. If it is estimated at the string level, then that is where charge management is applied. The functions in this subclause are written assuming that SOC is estimated for each cell as this is the most general case. If SOC is estimated in modules or strings, then those details are easily modified.

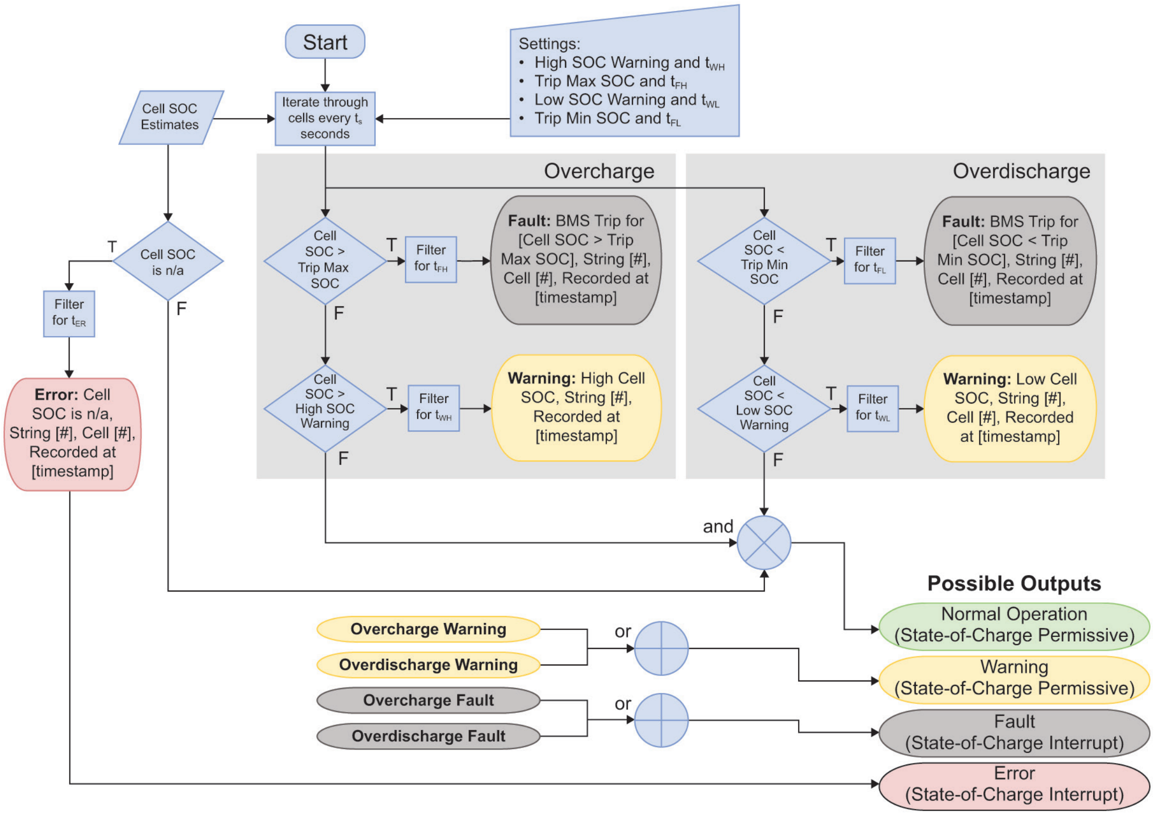

Figure 15—Example state-of-charge management process control diagram

4.5.8.2 Overcharge

— *Objective*: Prevent cells and strings from exceeding their maximum SOC.

— *Description*: In many battery types, overcharge can lead to early failure or a possible safety hazard. Depending on chemistry and operating conditions, it may be possible to charge a battery beyond its safe limits without violating one or more operational limits on voltage, current, or temperature. A BMS may provide overcharge protection by first reducing the operational charge current limit at or near Max SOC. However, if this is ineffective, the BMS should fault above trip max SOC. The operating SOC constraints may be dynamic, changing as a function of temperature, SOH, or operational states (e.g., if the battery is on a boost or equalizing charge) as determined by the manufacturer. Note that, as SOC should not exceed 100% by convention, the overcharge trip setpoint may be configured to operate on an internal SOC calculation that is able to exceed 100% (see 6.2.5). Depending on chemistry, overcharge interrupt constraints may be implemented based on current and/or voltage.

— *Inputs*: Estimated cell, module, and/or string SOC data

— *Settings*: high SOC warning, trip max SOC

— *Outputs*:

  — Normal Operation (SOC permissive) flag (true/false)

  — Error: Cell SOC is n/a, String [#], Cell [#], Recorded at [timestamp]

  — Warning: BMS Warning for: SOC [%] > High SOC Warning [%], String/Module/Cell [#], Recorded at [timestamp]

  — Fault: BMS Trip for: SOC [%] > Trip Max SOC[%], String/Module/Cell [#], Recorded at [timestamp]

4.5.8.3 Overdischarge

- *Objective*: Prevent cells from falling below their minimum SOC.
- *Description*: In many battery types, overdischarge can lead to early failure. Depending on chemistry and BMS operating parameters, it may be possible to discharge a battery beyond its safe limits without violating operational limits on voltage, current, or temperature. In grid supporting applications, a BMS may provide overdischarge protection by first reducing the operational discharge current limit at or near Min SOC. However, if this is ineffective, the BMS should fault below trip min SOC. The operating SOC constraints may be dynamic, changing as a function of temperature, SOH, or operational states (e.g., if the BESS is supporting a critical load through a power outage) as determined by the manufacturer. Note that, as SOC should not fall below 0% by convention, the overdischarge trip setpoint may be configured to operate on an internal SOC calculation that is able to fall below 0%.
- *Inputs*: Estimated cell, module, and/or string SOC data
- *Settings*: low SOC warning, trip min SOC
- *Outputs*:
  - Normal Operation (SOC permissive) flag (true/false)
  - Error: Cell SOC is n/a, String/Module/Cell [#], Recorded at [timestamp]
  - Warning: BMS Warning for: SOC [%] < Low SOC Warning [%], String/Module/Cell [#], Recorded at [timestamp]
  - Fault: BMS Trip for: SOC [%] < Trip Min SOC [%], String/Module/Cell [#], Recorded at [timestamp]

4.5.8.4 Unbalanced charge

See voltage imbalance function 4.5.5.4.

4.5.9 Flow battery management functions

4.5.9.1 General

The following flow battery management functions are applicable to batteries with flowing liquid electrolyte. These functions are applied in addition to (not instead of) voltage, current, temperature, and charge management (see 5.3.3).

4.5.9.2 Electrolyte flow management

4.5.9.2.1 General

Electrolyte flow management is a combination of electrolyte blockage detection and under pressure detection. Figure 16 shows an example process diagram for electrolyte flow management.

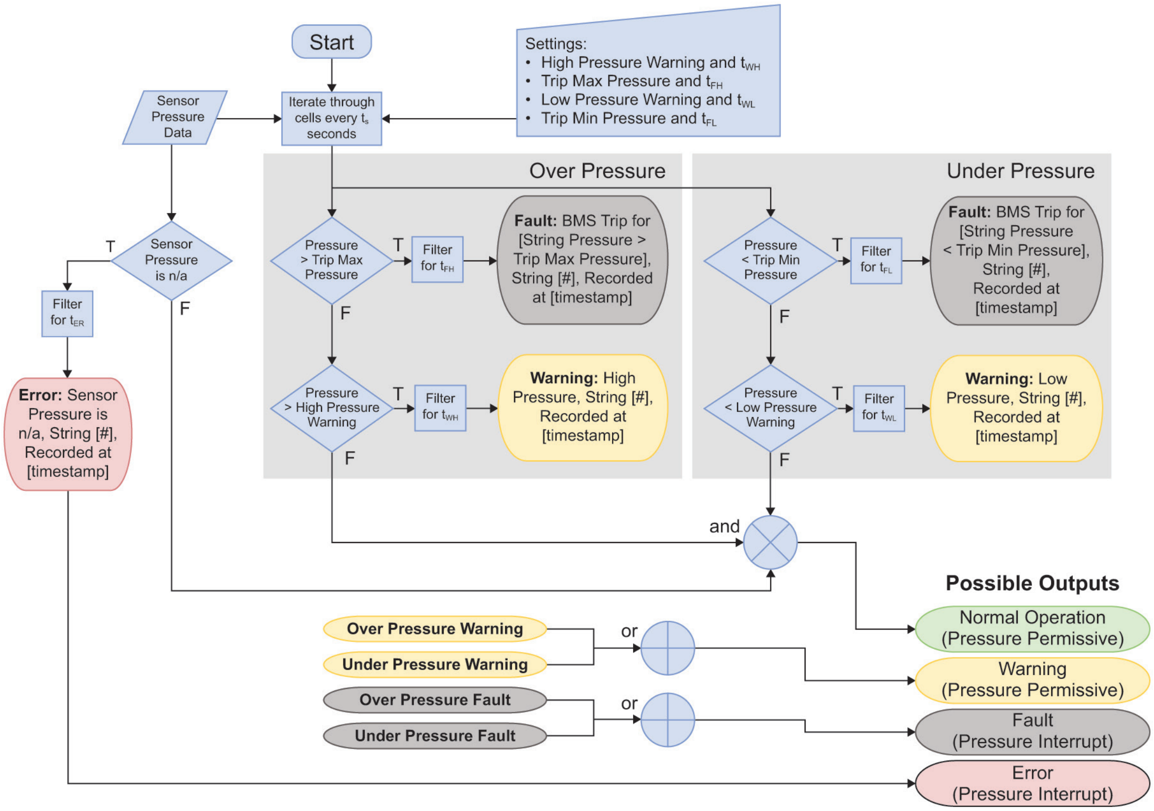

Figure 16—Example electrolyte flow management process flow diagram

4.5.9.2.2 Overpressure

- *Objective*: To detect a blockage within a stack that prevents or restricts electrolyte flow and to provide a status for the controller to take evasive action to stop the overpressure from occurring
- *Description*: The BMS monitors the electrolyte pressure at appropriate locations in the system to determine if there is a blockage indicated by pressure in excess of the trip max pressure. If a trip max pressure is reported by the BMS, the controller may isolate the affected string or shut down the system. If a partial blockage is detected by a pressure exceeding the max pressure, then the BMS reports a warning, and the controller may attempt to clear the blockage.
- *Input*: Pressure data
- *Settings*: high pressure warning, trip max pressure
- *Outputs*:
  - Normal Operation (Pressure permissive) flag (true/false)
  - Error: String Pressure is n/a, String [#], Recorded at [timestamp]
  - Warning: BMS Warning for: Pressure [P] > High Pressure Warning [P], String [#], Recorded at [timestamp]
  - Fault: BMS Trip for: Pressure [P] > Trip Max Pressure [P], String [#], Sensor [#], Recorded at [timestamp]

4.5.9.2.3 Electrolyte underpressure

- *Objective*: To detect a low pressure within a string or stack that could be indicative of a leak or pump issue and to provide a status to the controller to take evasive action.
- *Description*: The BMS monitors the electrolyte pressure at appropriate locations in the system to determine if there is a pressure below the trip min pressure. If a trip min pressure is reported by the BMS, the controller may isolate the affected string or shut down the system. If a min pressure is detected, then the BMS reports a warning.
- *Input*: Pressure data
- *Settings*: low pressure warning, trip min pressure
- *Outputs*:
  - Normal Operation (Pressure permissive) flag (true/false)
  - Error: String Pressure is n/a, String [#], Recorded at [timestamp]
  - Warning: BMS Warning for: Pressure [P] < Low Pressure Warning [P], String [#], Recorded at [timestamp]
  - Fault: BMS Trip for: Pressure [P] < Trip Min Pressure [P], String [#], Sensor [#], Recorded at [timestamp]

4.5.9.3 Spill/leak

- *Objective*: To detect electrolyte leakage into the secondary containment and shut down the pumps so that further leakage is minimized.
- *Description*: The BMS monitors for the presence of electrolyte in the secondary containment system. If electrolyte is detected, the pumps are shut down to minimize further leakage. A spill could be detected by level sensors or leak detectors that change resistance in the presence of electrolyte.
- *Input*: Level sensors or leak detectors in the spill containment system
- *Settings*: N/A
- *Outputs*:
  - Normal Operation (Spill permissive) flag (true/false)
  - Error: Spill Detection is n/a, Secondary Containment [#], Sensor [#], Recorded at [timestamp]
  - Fault: BMS Trip for [Spill Detected], Secondary Containment [#], Recorded at [timestamp]

4.5.9.4 Low electrolyte level

- *Objective*: To detect the loss of electrolyte from the system. A low electrolyte level could indicate electrolyte has evaporated and needs to be replenished or that electrolyte has leaked.
- *Description*: The BMS monitors the level of electrolyte in each tank in the system to determine if any electrolyte level is below the trip min electrolyte level. If a trip min electrolyte level is reported by the BMS, the controller may shut down pumps running in the affected tank or shut down the system. If a min electrolyte level is detected, then the BMS reports an electrolyte level warning.
- *Input*: Electrolyte level
- *Settings*: low electrolyte level warning, trip min electrolyte level

— *Outputs*:
  — Normal Operation (Electrolyte Level permissive) flag (true/false)
  — Error: Electrolyte Level is n/a, Tank [#], Recorded at [timestamp]
  — Warning: BMS Warning for: Electrolyte Level [L] < Low Electrolyte Level Warning [L], Tank [#], Recorded at [timestamp]
  — Fault: BMS Trip for: Electrolyte Level [L] < Trip Min Electrolyte Level [L], Tank [#], Sensor [#], Recorded at [timestamp]

4.5.9.5 Electrolyte tank temperature

— *Objective*: To detect an excessive electrolyte tank temperature and stop operation until temperatures are within the specified range.

— *Description*: The BMS monitors the temperature of the electrolyte in each tank in the system to determine if the temperature is above the trip max tank temperature. If a tank temperature interrupt limit violation is detected, then the BMS should interrupt operation of that string(s) or system to allow it to cool to a safe level. This is accomplished in several ways based on the design of a specific system but is often implemented through a circuit interrupt device (see 4.2.8.3). If a tank temperature warning limit violation is detected, then the controller may change the operational limits on charge and discharge power to allow the tank electrolyte to cool. With separate storage tanks for the electrolyte, it is possible for the electrolyte to exceed its maximum operating temperature requiring the system to be shut down while the stacks may have not overheated.

— *Input*: Electrolyte temperature in each tank

— *Settings*: high electrolyte temperature warning, trip max electrolyte temperature

— *Outputs*:
  — Normal Operation (Tank Temperature permissive) flag (true/false)
  — Error: Tank Temperature is n/a, Tank [#], Sensor [#], Recorded at [timestamp]
  — Warning: BMS Warning for: Sensor Temp [T] > High Tank Temp Warning [T], String [#], Sensor [#], Recorded at [timestamp]
  — Fault: BMS Trip for: Sensor Temp [T] > Trip Max Tank Temp [T], Tank [#], Sensor [#], Recorded at [timestamp]

4.6 Interactions with PCSs

There are three broad types of PCSs that interact directly with batteries and, hence, concern the BMS: ac-to-dc (e.g., charger or rectifier), dc-to-ac (e.g., inverter), or dc-to-dc. A bi-directional inverter acts as both an ac-to-dc PCS and a dc-to-ac PCS. PCSs have numerous control modes and functions. Three common control modes are constant voltage (CV) mode, constant current (CC) mode, and constant power (CP) mode on the dc side of the PCS. In these modes a feedback controller within the PCS measures the appropriate value, voltage, current, and power, and makes adjustments to reach and then maintain a stable setpoint.

While trying to achieve a setpoint, operational constraints are maintained. So, if under CP mode the power is set too high, such that a limit on charge current would be violated, the controller should reach the limit on charge current and then change to CC mode. Similarly, if a large discharge current is requested under CC mode, such that it would drive the battery's voltage below its limit, then the controller should reach the low voltage constraint and then change to CV mode (however, the BMS may adjust the operational constraint on current before the voltage limit is reached). Operational constraints should be coordinated between the PCS and the BMS, initially during commissioning and dynamically during operation, such that valid setpoints within the PCS's operational area do not violate interrupt constraints in the BMS.

5. Battery management configuration

5.1 General

Different battery systems have different battery management needs. Some battery types are more sensitive to abnormal operating conditions than others. Because of this, BMSs are configured by both anticipated use (application) and battery chemistry/formfactor (type). The BMS should be configured to allow the widest range of operation possible while preventing operational conditions that are unsafe, would make the battery unable to function for its application, or would result in accelerated battery degradation. Determining these precise limits for each battery type is an ongoing area of research and, therefore, manufacturers tend to be conservative when setting operational constraints within the BMS. Setting these operational constraints should be conducted according to the following general design principles:

— If an operational constraint is dependent on a known value (e.g., if max charge current is temperature dependent) then these limits should be dynamically adjusted as that value changes.

— If an operational constraint is dependent on an uncertain value (e.g., if temperature is known to within 5 °C), then the limit should be dynamically adjusted according to the worst-case value within its uncertainty.

5.2 Configuration by application

5.2.1 General

IEEE Std 1679™ [B25] lists several application considerations when an end user is determining the requirements for an intended application. Among these considerations are the power and energy requirements, the number of cycles to be supplied, and the design life.

The primary distinction in the configuration of a BMS between applications is the prioritization of these considerations. Some applications prioritize power and energy requirements (e.g., UPS backup), while others prioritize required life (e.g., batteries under warranty restrictions), and others balance these priorities operationally (e.g., energy market participation).

5.2.2 Grid supporting

5.2.2.1 General

A commonality of almost every grid supporting application is that the value derived from any one cycle is much less than the capital cost of the energy storage asset. Because of this, BMS parameters in such applications are chosen to preserve the battery's life, rather than forcing operation under suboptimal conditions.

Operational constraints on battery states should be configured to support battery longevity. These constraints should be imposed to have minimal impact on operations to minimize the difference between a device's power and its power setpoint. For example, if a worst-case discharge would drive the battery temperature to a level that would age the battery more rapidly, the BMS may cause the operational discharge current limit (and hence the heating effect) to be lower above a certain threshold temperature. Feedback on operational and interrupt constraints is diagrammed in Figure 17.

Multi-string battery systems are common in grid supporting applications. If a single string encounters an interrupt constraint in a multi-string system, the server BMS (4.2.4) should be configured to first update the operational constraints in the ESMS and/or PCS and then actuate the circuit interrupt device in that single string. Doing so prevents the remaining strings from being exposed to excessive charge or discharge current when the switch opens.

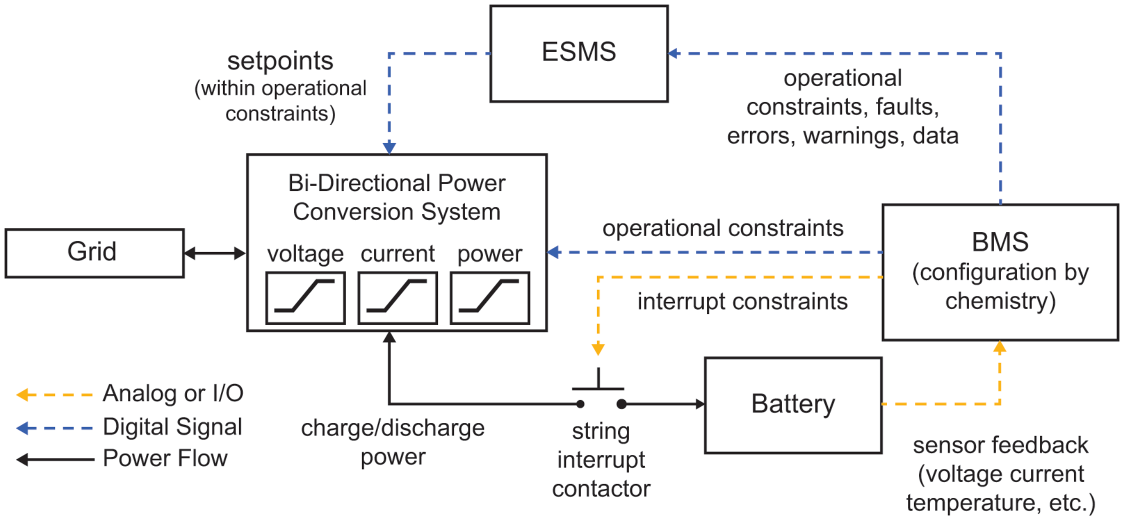

Figure 17—Feedback of operational and interrupt constraints in grid-supporting applications

5.2.2.2 Low-power, high-energy applications

Grid-supporting applications such as peak shaving, energy arbitrage, and renewable shifting have a low power-to-energy ratio. Battery energy storage systems performing such applications have power setpoints that change slowly and might take several hours to reach an operational constraint under a constant charge or discharge. In general, these systems have fewer localized heating issues and reduced thermal management costs. This means that it might be more cost efficient to have a lower temperature sensor density, provided that a single-cell thermal runaway event can still be detected, either by temperature sensing or by some other method such as vent-gas detection (see 4.2.8.10).

5.2.2.3 High-power, low-energy applications

Grid-supporting applications such as frequency regulation, primary frequency response, and power quality have a high power-to-energy ratio. Battery energy storage systems performing such applications have power setpoints that change quickly and can, under constant charge or discharge, reach an operational constraint rapidly. In general, these systems often have localized heating issues in the battery and higher thermal management costs. This means that it might be beneficial to have a higher temperature sensor density.

Many of these applications are performed at partial SOC and have high energy throughput. Such operation raises the importance of SOC estimation, making more accurate current sensing and a robust SOC-estimation algorithm highly desirable.

Because of the magnitude of current ramp rates that are applied to the battery, it may be advantageous to implement faster sample rates in the data acquisition layer and the battery management layer of the real time control computation stack (see 4.4.2).

5.2.2.4 Extreme service conditions

There may be some occasions where the value of a service provided by the BESS may justify a more extreme use profile, despite the accelerated battery degradation that may occur. Because of this potential, the BMS may be configured to dynamically adjust its operational and interrupt constraints as shown in Figure 18. These updated limits are triggered by a command from the ESMS, which can use them to expand the service. Constraints may be extended into regions of operation that can lead to accelerated degradation; however, the expanded operation should not lead to hazardous operation. This expansion should not change the limits that trigger warnings or errors reported to the user. This expansion should only change a limit that would trigger a fault for longevity functions for a given battery type as discussed in 5.3. Operation under extreme service conditions should produce warnings from the BMS.

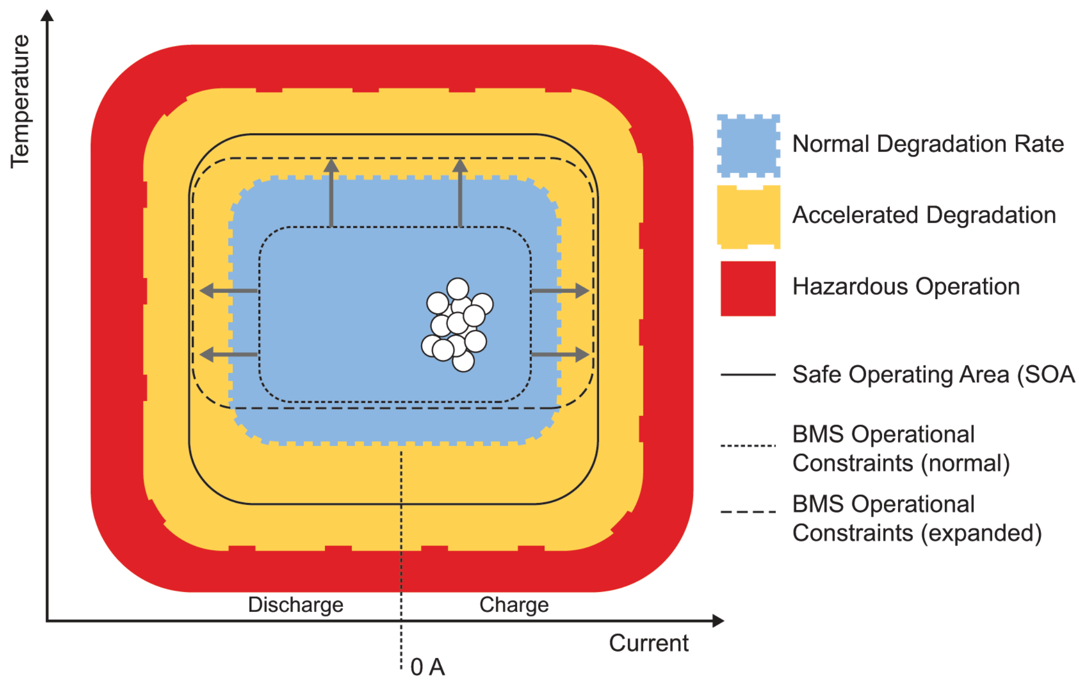

Figure 18—Illustration of dynamically expanded operational window under extreme grid conditions

5.2.3 Non-grid supporting

5.2.3.1 General

Non-grid-supporting applications generally fall into two categories: standby applications, where the battery system operates only when supply from the grid fails; and off-grid applications, in which the battery system is frequently operated in conjunction with a renewable-energy source, such as a photovoltaic system, and may be paired with a fossil-fueled generator (IEEE Std 1361™ [B19], IEEE Std 1561™ [B23]). BMS configuration for standby applications is discussed in 5.2.3.2. BMS configuration and operation for off-grid applications is similar to that for grid-supporting applications (see 5.2.2) because priority is placed on battery life over power and energy demands. The ESMS in off-grid applications is often configured to turn on a generator when battery SOC is low to recharge it but the BMS should be configured to prevent overdischarge regardless of ESMS operation (see 4.5.5.3 and 4.5.8.3).

5.2.3.2 Standby applications

5.2.3.2.1 General

Battery systems in standby operation are invariably used in critical applications, where the cost of a loss of power greatly exceeds the cost of the battery. In these cases, battery longevity is of secondary importance and the BMS operating parameters should allow continued discharge, even to the point of battery damage (although not to the point where such damage could result in a safety event). The configuration of a typical standby system and the operation of the BMS are shown in Figure 19.

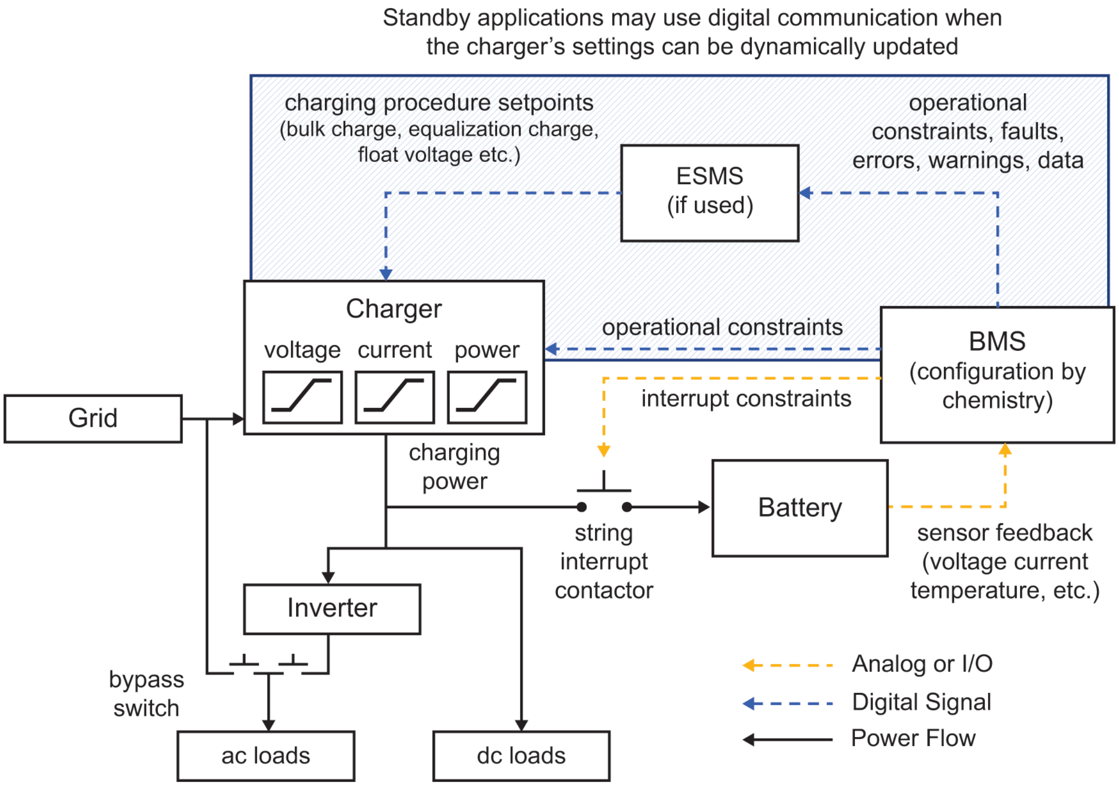

Figure 19—Feedback of operational and interrupt constraints in standby applications

In some cases, the charger may be a legacy unit designed for operation with lead-acid batteries and may not have a communications capability to accept operational constraints, in which case the BMS should be configured accordingly. For example, for operation with a legacy charger, the BMS may include a current-limiting function that mitigates excessive charging currents (see 5.2.3.2.2).

Discharge time requirements in standby operation vary by application. Two applications that represent opposite ends of the spectrum of discharge times, as well as widely differing dc voltages, are telecom (see 5.2.3.2.2) and uninterruptable power supply (UPS) (see 5.2.3.2.4). Substation applications (see 5.2.3.2.3) have similar discharge times to telecom applications.

Multi-string systems are normal in standby applications to improve availability. On discharge, the BMS is configured to open the current-rated switch (see 4.2.8.3.1) of the battery based on cell or battery voltage limits (see 4.5.4). In a multi-string system, it is never guaranteed that all strings will open at precisely the same time, even if signaled to do so, so the last string to open can be exposed to a discharge current that greatly exceeds the rating of its power switches, resulting in damage. To avoid this, the installation should include a single current-rated switch that is actuated before the current to be interrupted exceeds the combined limits for the remaining online battery strings. Because the conditions of connected load and number of operating battery units is often quite dynamic and could be affected by externalities such as temperature, the server BMS (see 4.3.3) should make the assessment of when to trigger the current-rated switch and should send the signal to do so.

5.2.3.2.2 Telecom applications

Telecom systems typically operate at 48 V dc, and battery discharge times are frequently in the range of 4 h to 8 h. Alternative battery technologies offered for such applications, such as lithium-ion and sodium-nickel chloride, are often configured as 48 V unitized battery systems with embedded BMSs. The high energy density and low current (as a function of rated capacity) of these battery systems and the need to minimize auxiliary power consumption favors the use of semiconductor MOSFETs, rather than contactors (see 4.2.8.3). While communications with the battery system may be enabled for alarm management, there is typically little or no coordination with the host system for control of either charging or discharging.

Telecom powering architecture typically involves installation of multiple battery strings in parallel, and charging power is provided by rectifier shelves with multiple parallel rectifier units. This presents battery-management challenges in both charging and discharging.

It is not unusual for a new outside plant cabinet to be configured with a fully populated rectifier shelf, even though the initial connected load may be quite low. Battery installation typically reflects the connected load, so a cabinet that can accommodate, for example, 6 battery units may be initially populated with only 2 units. This means that the available current for battery charging can greatly exceed the manufacturer's limits for charging. While the rectifier plant may include a software-based battery charging current limit, there is no guarantee that this will be set correctly for the number and type of battery units connected. Therefore, the BMS in the battery units should include a current-limiting function that should be engaged if the charging current exceeds the battery limit. For example, a resistor could be switched in series with the battery to provide sufficient voltage drop to limit the charger output to an acceptable level. The resistor would have a diode in parallel to allow discharge current to flow until the main current path can be restored, thus bypassing the current-limiting resistor.

5.2.3.2.3 Substation applications

In substation applications, the most common operating voltages are 125 V and 250 V dc nominal. 250 V is often used in large power generation and substations. The battery typically feeds non-linear loads composed of high instantaneous currents for short periods of time (from milliseconds to several seconds, but less than a minute) and lower current steady loads for extended periods of time (typically 2 h to 8 h). The main challenge in these applications is the instantaneous current, which may exceed a single BMS protection limit capability. In this case, additional parallel BMS/batteries should be used even though the additional battery capacity would not be required. Because the substation load is known at the time of the substation design, battery capacity and the number of BMS are defined at the start. Adding parallel strings in the future is uncommon.

Two or more chargers can also be connected to a common battery so the available charging current can exceed the recommended level. In this case, a battery current limiting feature can be required in the charging circuit internal or external to the battery charger. An additional communication means between the charger and the BMS can be beneficial to help adapting the charging parameters to the battery conditions, such as the charger current and/or voltage reduction or shut down, to prevent undesired battery incidents.

5.2.3.2.4 Uninterruptable power supplies (UPS)

UPS systems in data centers typically include a battery operating at a nominal voltage of 480 V dc. Such batteries often employ a modular architecture with separate BMSs. Multiple parallel strings are typically installed on a common dc bus, with their operation coordinated by a server BMS or multi-string controller as discussed in 4.2.4.

Specified discharge times of 5 min or less are not uncommon, resulting in high discharge currents, relative to battery capacity, per string. String disconnection and reconnection is generally accomplished using contactors, rather than semiconductor switches (see 5.2.3.2.2). For redundancy, the rating of all current-carrying components, including those in the BMS, should be sized to support operation with one parallel string out of operation. True BMS redundancy is infeasible in most UPS applications. Instead, UPS systems rely on string redundancy or full UPS redundancy. Where a redundant BMS is used, a failure in one of the BMSs should trigger a seamless hand-off to the redundant BMS without interrupting UPS operation.

Actual discharge times in data centers are normally limited to less than the specified time by the starting of standby generation. Failure of that generation can result in more prolonged discharge, with potential issues relating to disconnection at the end of discharge. Newer UPSs often have a communications capability that allows them to interface with a BMS for charge control, in which case the charge current can be limited within the battery's constraints. UPS discharge should be terminated just before the parallel strings open their current-rated switches (see 4.2.8.3.1) for safety reasons. If a UPS is not set correctly, a longer discharge could lead to uncoordinated string disconnection, damage to contactors, and/or opening of protective devices.

In industrial applications, the UPS operation is almost the same as in data centers with the exception that the dc bus can be 125 V dc and the most common back up time is 1 h to 2 h.

5.3 Configuration by battery type

5.3.1 General

The environmental and operational limits for batteries can generally be found on the manufacturer's specification sheet. Generally, these limits are based on the material properties of battery and on testing to determine the rate of degradation under different operational conditions. When reading battery specification sheets, keep in mind that assumptions about their operational environment and use can sometimes go unstated. As an illustrative example, consider a battery manufacturer with two products: a long-life battery with a low maximum charge rate and a fast-charging battery with a shorter expected life. While it is not common to do so, these two products could be physically identical batteries. The difference between them would not necessarily be in the material properties of the batteries but could be in the configuration of the BMS. The long-life battery's BMS would be configured to restrict the maximum charge rate while the fast-charging battery's BMS would allow higher-rate charging.

The BMS is responsible for providing both operational constraints and interrupt constraints (see Clause 3).

5.3.2 Lithium-ion batteries

This subclause identifies the battery management functions that are recommended for lithium-ion battery systems. A description of the active management requirements for lithium ion batteries can be found in 5.8 of IEEE Std 1679.1™-2017 [B26]. Lithium-ion battery systems should implement the following battery management functions:

— Voltage management. See 4.5.4. Overvoltage and undervoltage management are safety functions and should be implemented on each cell in the system. Voltage imbalance management is a longevity function and should be implemented on each string in the system.

— Current management. See 4.5.6. Overcurrent management is a safety and longevity function and should be implemented on each string in the system. Parameters can be adjusted based on temperature and SOC. This function is in addition to short-circuit overcurrent protection that should be implemented in each module with an appropriately sized circuit breaker or fuse.

— Temperature management. See 4.5.7. Overtemperature, undertemperature, and temperature imbalance management are longevity functions and should be implemented on each module in the system. The battery system should be designed to be robust to failures of the thermal control system, for example, by reducing or blocking current flow, such that the thermal control system is not essential to the safety of the overall system.

— Charge management. See 4.5.8. Overcharge and overdischarge management are safety and longevity functions and should be implemented on each string in the system. Unbalanced charge management is a longevity function and should be implemented on each string in the system. The BMS and the ESMS provide redundant overcharge protection. Cell charge balancing is an important BMS function for most lithium-based chemistries but is implemented through voltage imbalance management (see 4.5.5.4).

Lithium-ion battery systems may include vent-gas detection (see 4.2.8.10) implemented through the fire alarm system or the BMS. Thermal runaway vent gas detection and response is a safety function and may be implemented on each enclosure in a system. This function can be critical when batteries are installed in indoor, poorly-ventilated spaces.

If any of the implemented functions trigger an interrupt constraint the BMS should take the following actions:

a) OPEN the associated battery string current-rated switch (see 4.2.8.3.1).

b) Set the current operational state of the associated battery to FAULT or ERROR.

c) Log the fault or error and elevate it to the ESMS.

d) Continue to log data and wait for a command to reset faults or errors.

5.3.3 Flow batteries

This subclause identifies the battery management functions that are recommend for flow battery systems. Flow battery systems should implement the following battery management functions:

— Voltage management. See 4.5.4. Overvoltage and undervoltage management are safety functions and should be implemented on each cell system. Voltage imbalance management may be implemented but is not specifically recommended.

— Current management. See 4.5.6. Overcurrent management is a longevity function and should be implemented on each string in the system. Excessive current can lead to high heat generation in electrolyte that accelerate component degradation rates. This function is in addition to short-circuit overcurrent protection that should be implemented in each module with an appropriately sized circuit breaker or fuse.

— Charge management. See 4.5.8. Overcharge and overdischarge are safety functions and should be implemented on each string in the system. The BMS and the ESMS provide redundant overcharge protection. Overcharging a flow battery could lead to unwanted gas formation within electrolyte tanks.

— Flow battery management. See 4.5.9. Electrolyte flow management, spill/leak management, low electrolyte level management, and electrolyte tank temperature are both safety and longevity functions and should be implemented on each tank/pump in the system. Electrolyte leaks can be hazardous and may require personal protective equipment to clean up. Hot electrolyte can have reduced performance or efficiency.

Flow battery systems may include hydrogen-gas detection (see 4.2.8.9) implemented through the fire alarm system or the BMS. If any of the implemented functions trigger an interrupt constraint the BMS should take the following actions:

a) OPEN the associated battery string current-rated switch (see 4.2.8.3.1).

b) Turn OFF all pumps and, if applicable, return the system to an inactive safer state.

c) Set the current operational state of the associated battery to FAULT or ERROR.

d) Log the fault or error and elevate it to the ESMS.

e) Continue to log data and wait for a command to reset faults or errors.

5.3.4 Sodium-β batteries

This subclause identifies the battery management functions that are recommended for sodium-β battery systems. A description of the active management requirements for sodium-β batteries can be found in 5.8 of IEEE Std 1679.2-2018 [B27]. Sodium-β battery systems should implement the following battery management functions:

— Voltage management. See 4.5.4. Overvoltage and undervoltage management are safety functions and should be implemented on each cell in the system. Voltage imbalance is a longevity function and should be implemented on each string in the system.

— Current management. See 4.5.6. Overcurrent is a safety function and should be implemented on each string in the system. Unbalanced charge is a longevity function and should be implemented on each string in the system. Parameters can be adjusted based on temperature and SOC. This function is in addition to short-circuit overcurrent protection that should be implemented in each module with an appropriately sized circuit breaker or fuse.

— Temperature management. See 4.5.7. Overtemperature, undertemperature, and temperature imbalance are longevity functions and should be implemented on each module in the system. The battery system should be designed to be robust to failures of the thermal control system, such that the thermal control system is not essential to the safety of the overall system. Sodium-β batteries are designed to operate at elevated temperatures above the melting point of the metallic sodium. In the event the battery temperature falls below its operating range, the cell resistance increases due to reduced ion mobility. The BMS should be designed to notify the user when temperature management fails and prevent permanent damage to the battery, although this condition can result in loss of ability to provide energy.

— Charge management. See 4.5.8. Overcharge and overdischarge management are safety functions and should be implemented on each string in the system. Unbalanced charge is a longevity function and should be implemented on each string in the system. The BMS and the ESMS provide redundant overcharge protection. Cell charge balancing is an important BMS function for most sodium-based chemistries but is implemented through voltage imbalance management (see 4.5.5.4).

If any of the implemented functions trigger an interrupt constraint the BMS should take the following actions:

a) OPEN the associated battery string current-rated switch (see 4.2.8.3.1).

b) Set the current operational state of the associated battery to FAULT or ERROR.

c) Log the fault or error and elevate it to the ESMS.

d) Continue temperature management to keep the batteries in their operating temperature range.

e) Continue to log data and wait for a command to reset faults or errors.

5.4 Qualification

5.4.1 General

BMS qualification is a two-step process. First, the BMS and its software are qualified in accordance with relevant standards. Second, BMS functional safety is verified as part of the battery system, in accordance with the battery-level standard.

In North America, the BMS is qualified to UL 991 [B53], UL 1998 [B55], and CSA/ANSI C22.2 NO. 340:23 [B5]. Battery-level certification testing is performed in accordance with UL 1973 [B54].

In other parts of the world, BMS qualification is to the IEC 61508 family of documents [B14] and/or IEC 60730-1 [B11]. The umbrella standard for Li-ion battery qualification in industrial applications is IEC 62619 [B17], with specific requirements for energy storage applications (including standby) in IEC 63056 [B18].

5.4.2 Electromagnetic compatibility

Electromagnetic compatibility (EMC) comprises immunity to electromagnetic disturbances and the limiting of emissions within problematic frequency bands. The IEC 61000 series of standards [B13] and, in the US, FCC – 47 CFR Part 15 [B1] and FCC – 47 CFR Part 18 [B2], are written to make sure that a device 1) doesn't interfere with other devices, and 2) accepts interference from other devices.

5.4.3 Alkaline and aqueous batteries

Generally, lead-acid batteries and many similar battery types do not use a BMS due to their inherently stable operation, low energy density, non-flammable electrolyte, wide temperature operating range, and relatively wide charging voltage range. Overcurrent and short-circuit damage can be prevented by an appropriately specified circuit-breaker or fuse. As such, they typically do not need the tight charge, discharge, or operating controls provided by a BMS.

Aqueous battery systems may implement the following battery management functions:

- Voltage management. See 4.5.4. Overvoltage and undervoltage management are longevity functions and may be implemented on each string voltage or on each cell voltage.
- Charge management. See 4.5.8. Overcharge and overdischarge management are safety functions and may be implemented on each string in the system. The BMS supervises the charger to provide redundant overcharge protection. Overcharging an aqueous battery could lead to excessive hydrogen gas formation and, in extreme cases, thermal walkaway.
- Hydrogen gas detection. See 4.2.8.9. Hydrogen gas detection can be implemented as a standalone device, through the fire alarm system, or thrugh the BMS. Hydrogen gas detection and response is a safety function and may be implemented on each enclosure in a system.

6. Communications and interoperability

6.1 General

This clause describes the interface of the BMS with other components of a BESS, with the ESMS, and with other external elements such as network operations centers or cloud-based databases. The BMS is responsible for supplying information that is critical to the safety and longevity of the battery to automated and human controllers that need it. The simplest example of this operation is for it to be performed manually by a technician. For example, a battery's minimum voltage can be read manually from the BMS interface and set manually in the PCS's interface. However, many operational constraints and battery states change dynamically and, therefore, should be updated automatically. For example, operational constraints for charge current change with temperature and SOC. Providing this current and the battery voltage to the ESMS can enable it to optimize the battery's operation in real time. Providing cell outliers to the battery owner can enable them to perform more efficient maintenance. These example BMS information functions are not self-contained battery management functions as discussed in 4.5 because as they do not include actuation but they can still be important for safe and effective battery operation.

This clause is organized as follows: 6.2 covers an array of specific BMS information functions; 6.3 discusses the general information and control bus including protocols and data formats used to communicate with a BMS; 6.4 discusses the diagnostic and reconfiguration bus; and 6.5 discusses best practices for BMS cybersecurity including firmware updates.

6.2 BMS information functions

6.2.1 General

A BMS can supply information to owners, operators, maintenance technicians, or external devices that can use accurate information from the battery to make decisions. The information supplied depends on the external entity and the decision(s) to be made. A device owner may use the reported SOH to plan when to replace or refurbish the battery. Maintenance technicians could use cell voltage data to decide if any cells need to be replaced to maintain reliability. An ESMS may use the reported SOC to optimize the battery's charge and discharge. The set of external agents to consider is different by application as discussed in 5.2 with the primary distinction being between grid supporting and non-grid supporting. This subclause provides recommendations on the type of information that is useful to different external agents and how to make that information available to them.

6.2.2 External agents and devices

This subclause provides a list of external agents and devices that interact with battery systems in different ways and have different informational needs when doing so. Examples are given in Table 2.

Table 2—Example external agents and devices

Name	Decisions/processes	Data/information requirements
ESMS	The ESMS uses the battery's current state to determine its limits of operation. At the most basic level the ESMS needs to receive up-to-date state information at the same sample rate it makes dispatch decisions. The sample rate and the latency requirements are based on the application.	Battery ratings (e.g., capacity), battery states (e.g., SOC), operational constraints
Device owner	The device owner is primarily interested in the aggregate performance of the battery. The owner needs to know how quickly the battery's performance is degrading and when it will need to be replaced.	SOH, predicted EOL
Device operator or Performance analyst	The device operator needs to understand how the battery is operating, if there are any problems, and how it might be operated better.	Operating status, faults, and warnings, cumulative throughput[a]
Maintenance technician	Maintenance technicians have a range of tasks depending on the battery type and its application. The often utilize a diagnostic port or bus with access to more detailed information than what the BMS makes available to the ESMS.	SOC, cell voltages, cell resistances (if applicable), cell temperatures, faults and warnings, ground fault resistance
Post incident analyst	After an accident the BMS can be used to determine what happened.	Historical log of SOC, cell voltages, cell resistances (if applicable), cell temperatures, faults, and warnings

[a]cumulative throughput refers to the sum of discharged kilowatt-hours or ampere-hours over the life of the battery (see 6.2.6.2).

6.2.3 Measurement accuracy

This subclause describes the minimum measurement and calculation accuracy recommended for battery management. These minimums apply to the data acquisition layer of the real-time control computation stack discussed in 4.4.2. Some BMS applications require much faster sample rates than those specified here. Batteries being used for power quality applications, for example, may require that protective actions be applied at a time scale faster than the duration of a power system disruption. As discussed in 3.2, high measurement uncertainty can make enforcing an SOA more difficult. Conversely, more precise measurements can slightly improve performance by narrowing the margin for error when enforcing an SOA. Table 3 details

Table 3—Battery energy storage recommended minimum measurement and calculation accuracy recommendations for manufacturers

Parameter	Minimum measurement accuracy	Measurement window (1/sample rate)	Range
Cell voltages	± 10 mV (8 bits/cell)	200 ms	0–5 V
Module voltages (if used)	(± 1% V_{nom}[a])	200 ms	$V_{min} - V_{max}$ (module voltage)
String voltages	(± 1% V_{nom}[a])	200 ms	$V_{min} - V_{max}$ (string voltage)
Cell/module temperatures	± 0.2 °C	1 s	−40 – 80 °C
String currents	(± 2% I_{rated})	200 ms	$I_{max\text{-}discharge} - I_{max\text{-}charge}$ (string current)

[a] V_{nom} refers to the nominal voltage of a given battery and application.

Measurement noise can substantially impact accuracy, but this impact can be difficult to diagnose. Using an oscilloscope with a high sample rate can often help identify when electrical noise is causing high measurement error. A common source of measurement noise in batteries connected to power systems is from the power lines themselves. This noise appears in data acquisition at 50 Hz or 60 Hz (and any line harmonics), depending on local grid frequency, and is one reason why data cables and power cables should generally be separated. A second source of measurement noise is the PCS itself. Single-phase PCSs often add a large ac waveform, at double the line frequency, to the dc bus when charging or discharging. Additionally, the high frequency switching involved in pulse width modulation within the PCS can generate electromagnetic noise. These sources of noise can affect lower sample frequency measurements if not properly filtered out. For example, consider a battery being charged from a single-phase inverter with an average current of 10 A. The ac current on the dc bus is 10 A peak-to-peak, meaning that the current is alternating between charging at 5 A and 15 A at a frequency twice the grid frequency. If a measurement of dc current only takes a millisecond, then that snapshot will randomly return some value between 5 A and 15 A. This phenomenon is called aliasing.

To reduce the likelihood of measurement corruption through aliasing, the BMS may either have an anti-aliasing analog filter on the input to each of its electrical measurement channel or it may have a sample rate at least double the frequency of any large sources of noise and digital filter.

6.2.4 Event notification

Faults, warnings, and errors can be automatically reported to an ESMS or a designated operator. To minimize downtime, BMSs should be able to be configured on a network to send automatic notifications of such events. Notifications to individuals or groups may be supplied via text message to mobile phones, email, pager, or any other means of direct communication. A BMS heartbeat (see 4.4.6), should be used as a means of continuously verifying its ability to send event notifications.

6.2.5 State of Charge (SOC)

6.2.5.1 General

SOC is an estimated quantity defined in IEEE Std 1881™- 2016 [B29] as “The stored or remaining capacity in a battery expressed as a percentage of its fully charged capacity.” This is related to, but not the same as, the electrochemical definition of SOC which is a function of the concentration of the limiting active ionic materials associated with the chemical reactions at the electrodes (Plett, G. L., [B46]. See 4.4.2 of IEEE Std 1547.9™-2022 [B22] for a description of how the raw SOC reported by the BMS may be used/interpreted by external agents. Figure 20 shows a process flow diagram for estimation of SOC. The BMS collects physical measurements from the battery (see 4.2.3) and feeds them into a physical model of the battery to estimate the potential energy state in relation to the fully charged and fully depleted states. The same physical model used for estimating SOC can be used to calculate other values such as available energy, run-time, or available power. This model can also be used to implement state-feedback control in some grid supporting applications.

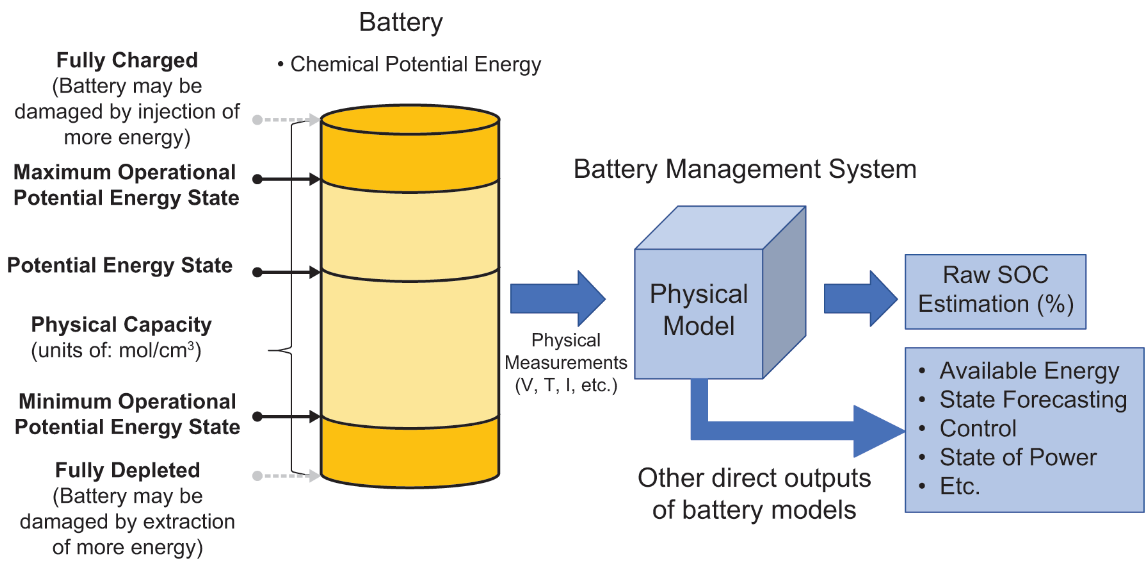

Figure 20—Model based estimation of SOC (subset of Figure 2 in 1547.9–2020 [B22])

State-of-charge is generally calculated differently depending on the battery type. This is because different battery types have different models that relate their physical measurements to their SOC. Physical modeling in general and SOC estimation in specific are an active area of research and development (see Espedal, L.B., et al. [B7], Xiong, R., et al. [B57], and Hu, X., et al. [B10]).

One common method of SOC estimation that is used in many physical models is coulomb counting [Equation (1)]. This model works on the principle that changes in chemical concentration within the battery will be proportional to the ampere-hours that pass through the circuit. A coulomb is one ampere-second and is proportional to the number of ionic state changes within the chemistry of the battery.

$$SOC = 100\,\% \times \left(1 + \frac{1}{C(SOH)} \int_{t_0}^{t} I^{-}(t) + \eta\, I^{+}(t)dt\right) \tag{1}$$

where

$C(SOH)$	is the rated capacity as a function of state of health (SOH)
I^{+}	is the charge current (positive values by convention)
I^{-}	is the discharge current (negative values by convention)
η	is the coulombic efficiency (close to unity for lithium-ion batteries)
t_0	is most recent time the cell was known to be at its fully-charged capacity

Coulomb-counting can be used in an electrical model of the battery to predict measurable values such as runtime and I-V performance (see Chen, M., et al. [B4]). Battery electrical models commonly use equivalent circuits to represent different chemical processes as resistors and capacitors and other circuit elements (see Rosewater, D.M., et al. [B49]).

Comparing the accuracy of different models used to calculate SOC is challenging because SOC is an estimated and not a measured value. It is common to establish operational states where SOC is defined to be a specified value (e.g., an open circuit voltage of X is defined to be 100% SOC). These defined states can be used to validate model accuracy and recalibrate the SOC. When the physical model is used to predict measurable values, the accuracy of these predictions (e.g., voltage error or runtime error) should be used to compare model accuracy (see Chen, M., et al. [B4]).

Below is a list of best practices for reporting SOC to a user or an ESMS. These aggregate properties of the SOC signal make it more usable by controllers and more understandable to operators. A review of SOC estimation methodologies for various battery types can be found in Xiong, R., et al. [B57].

- The SOC should be reported as a percentage of the fully charged capacity. Fully charged capacity can change over time due to degradation.
- The SOC should never be reported below 0% or above 100%. The internal SOC calculation may use values outside this range for interrupt constraints (see 4.5.8.2 and 4.5.8.3) but these should not be reported.
- The SOC estimation algorithm should be well tuned over its whole SOC and temperature range. The reported SOC should be smooth, meaning that the maximum difference between sequential estimates should be limited by the maximum theoretical change in state of change between time steps. Smoothness can be relaxed when an algorithm first starts or when cells, modules, or strings are added to or removed from the estimate. A state of change estimate that violates smoothness can be a sign of either poorly tuned algorithm parameters or inaccurate input data.
- During PSOC cycling with limited resting periods, it is necessary to estimate SOC by coulomb-counting. This requires accurate knowledge of the battery SOH (see 6.2.6), therefore, the battery should be periodically tested and the SOH updated to reduce estimation errors.
- SOC estimation errors also accumulate during coulomb-counting due to sensor inaccuracy. SOC can be recalibrated when there is a period of very low or no current flow if the battery is in a zone where the open-circuit voltage is indicative of SOC. In chemistries with flat voltage curves, this may require that a string or strings be taken out of service and brought to such a zone. SOC recalibration should occur automatically as part of the SOC algorithm. SOC changes resulting from recalibration should be made smoothly. The BMS should track the time from the last calibration and send a warning when a threshold time is exceeded.
- The SOC and capacity calculations, along with their parameters, should be made available to the device owner. Smoothness should be maintained when recalibrating SOC using voltage readings to prevent sudden jumps that could trigger actions based on SOC thresholds.

6.2.5.2 SOC aggregation

There are several methods that may be used to aggregate the SOCs from individual cells, modules, and strings to full systems. For applications where all parallel strings are required to support the load, the aggregate SOC should equal the lowest SOC measured on any of the parallel strings. This is because once the first string violates an interrupt constraint, the whole battery may be unable to support the load. If there is one redundant string, then the aggregate SOC should equal the second lowest SOC measured on any of the parallel strings. This method enables accurate estimation of available discharge energy using a very simple calculation (SOC × fully-charged kWh capacity of the battery).

In grid supporting applications, SOCs from individual cells, modules, and strings can simply be averaged to calculate a system SOC. This approach is appropriate for systems with effective voltage imbalance management (see 4.5.5.4).

Alternatively, for grid supporting and cycling off-grid applications the BMS can base the aggregate SOC on a dynamic capacity aggregation. Dynamic capacity aggregation works on a principle that a distribution of cell SOCs within a string has the net effect of a reduced useable capacity. The gap in charge between the highest SOC cell and lowest SOC cell is subtracted from the total capacity to calculate useable capacity. The aggregated SOC is then the minimum SOC, multiplied by the total capacity divided by the usable capacity. This operation renormalizes the SOC to the useable capacity.

NOTE—Example: A string of 100 Ah battery cells has a distribution of SOCs from 80% to 85%. The useable capacity is 95 Ah (100Ah × (100% - (85% - 80%)) = 95 Ah). The aggregated SOC of the string is then 84.21% (80% × 100 Ah ÷ 95 Ah = 84.21%). To check this result, we can calculate the available discharge capacity and charge capacity using the calculated SOC. The discharge capacity is 80 Ah (84.21% × 95 Ah = 80 Ah) and the charge capacity is 15 Ah ((100% - 84.21%) × 95 Ah = 15 Ah). These results match the available discharge and charge capacities of the original given the distribution of cell SOCs.

6.2.6 State of Health (SOH)

6.2.6.1 General

For any battery technology for which the available capacity degrades over time, the BMS should calculate quantitative SOH. SOH is defined in IEEE Std 1881™- 2016 [B29] as "A measurement representing the present state of battery available capacity or remaining service life relative to rated capacity or specifications." The SunSpec Model Reference [B50] defines SOH as the "ratio (expressed as a percentage) of the current rating of the battery with respect to the nameplate rating of the battery and end of life criteria." Like SOC, quantitative SOH is typically expressed as a percentage. SOH is commonly calculated by dividing the current useable capacity by rated capacity. SOH can be measured directly, though doing so normally takes a standardized charge and discharge cycle, which interrupts normal operation. In between direct measurements, a BMS can estimate SOH through a variety of algorithms based on operational data. For example, as discussed in 6.2.5.1, SOC calculation by coulomb counting requires knowledge of the SOH, so errors in SOC during recalibration can be used to infer the SOH.

A second common definition of quantitative SOH is the percentage of progress from beginning of life (BOL) to end of life (EOL). This definition requires that an EOL capacity be defined, and that the SOH reported by the BMS counts down from 100% at the BOL to 0% when the EOL capacity is reached. This implementation also means that a change in battery mission, in which the available capacity is allowed to degrade to a lower level than that originally defined, requires that the SOH be recalculated based on the new EOL capacity.

When quantitative SOH is reported to a user or external device, the following practices are recommended:

- The SOH should be reported as a percentage. An explanation of what this percentage is intendedto represent or predict, including any calculations, should be provided to the owner.
- The SOH should never be reported below 0% or above 100%. If there is an internal calculation that needs to use a state of health like value outside of this range (e.g., some battery types that increase in capacity for the first few months of operation), then it should be tracked separately from the state of health.
- The SOH estimate should be manually adjusted whenever the test to measure it is performed. A record should be kept of the last time a test was performed.
- If the BMS is integrated with a battery, the SOH estimation algorithm along with its parameters should be made available to the battery owner. Additionally, providing this model to the ESMS can allow the battery to be operated in such a way as to minimize degradation.
- Capacity tests to verify SOH should be performed on a specified schedule depending on battery type and application.

6.2.6.2 Throughput

A simplified calculation that is related to remaining service life is to compare the battery's cumulative throughput to its rated throughput. Throughput is commonly used in performance guarantees and warrantees. Throughput is not an accurate measure of SOH, outside of a very narrow range of operation.

Rated throughput is the total energy (kWh) or charge (Ah) that can be discharged during the entire life of the battery. Rated throughput can be calculated using [Equation (2)]

$$\text{Rated throughput} = \text{Battery capacity} \times \text{Cycle life} \times \text{Depth of discharge} \qquad (2)$$

where

Battery capacity	is given in energy or charge
Cycle life	is the number of cycles the battery is rated to provide before EOL at the specified depth of discharge (DOD)
Depth of discharge	is the percentage of energy or charge removed in each cycle

For example, a 10 kWh battery rated to be able to provide 1000 cycles at 80% depth of discharge would have an 8 MWh rated throughput. Cumulative throughput is the sum of discharged kilowatt-hours or ampere-hours over the life of the battery. Cumulative throughput can be calculated using one of the following equations [Equation (3) and Equation (4)]:

$$\text{Cumulative throughput (Ah)} = \int I(t)\,dt \quad \forall I(t) > 0 \qquad (3)$$

$$\text{Cumulative throughput (kWh)} = \int P(t)\,dt \quad \forall P(t) > 0 \qquad (4)$$

where

I is the battery current, with positive values of each indicating discharge
P is the battery power, with positive values of each indicating discharge

The SOH can then be estimated as one minus the ratio of cumulative throughput to rated throughput. For example, using this method a battery with an 8 MWh rated throughput that has discharged 2 MWh over its life has a percent remaining service life SOH of 75% [100% × (1 MWh – 2 MWh ÷ 8 MWh)].

6.2.7 Data-driven predictive maintenance

Some of the information collected by a BMS can be used to efficiently schedule system maintenance. For some battery types, cells or modules that experience rapid degradation can be replaced before they start to limit system performance. A ground fault detection circuit can identify a gradual formation of a ground fault long before a hazardous condition is present. A maintenance plan can include automated reporting of information from the BMS to facilitate predictive maintenance.

6.3 General information and control bus

6.3.1 General

A BMS should have provisions for a BMS general information and control bus capable of communicating to support the information exchange requirements specified in this document. Information from a BMS, such as the battery's SOC, can be used by a site controller or ESMS to supply energy services or for many other purposes. Additionally, a BMS can have provisions for the BMS general information and control bus to be capable of communicating more and more detailed information as needed. These data should be interoperable such that they are provided in a standardized format using standardized communication protocols. This contrasts with the diagnostic and reconfiguration bus described in 6.4.

A BMS should be designed for easy and seamless integration into most networks. The BMS should be able to both send and receive data over the network. BMS data exported to an external cloud-based database or digital twin (see Annex C) can also be used for battery analytics. The structure and method of accessing these data should be specified and, if possible, should conform to a published standard.

A BMS should implement the standardized data structure specified by the SunSpec Information Model [B51] to the extent practical. This model specifies the length and arrangement of data registers that hold relevant data for a generic battery as well as for several specific battery types. Making operational data available in a standardized format can reduce integration time and avoid costly integration mistakes. Included in this recommended practice are a few additional points that are useful in specific devices and/or applications.

The data access structure used for battery data should match the physical structure of the battery itself. Aggregate calculations should then be based only on those lower-level structures that are connected and operational. This practice enables modularity. There should be the following discrete data structures:

- One data structure for the system as a whole.
- If there are multiple independently controllable batteries:
  - One data structure for each independently controllable battery.
- If there are multiple strings:
  - One data structure for each string.
- If there are multiple modules:
  - One data structure for each module which holds battery cell data.

Each data structure should contain the states and operational constraints of the battery it represents. This leads to some redundancy in memory. For example, both a string data structure and a module data structure hold values for the highest cell voltage and the maximum cell voltage constraint.

The SunSpec Information Model [B51] organizes battery data into a Battery Base Model structure and a range of technology specific models. For example, a large Li-ion battery system could have its BMS data organized as follows:

- One Battery Base Model (802)
- One Battery Bank Model (803) for each independently controllable battery grouping (e.g., parallel ISO containers connected to the same PCS)
- One String Model (804) for each parallel battery string
- (Optionally) one Module Model (805) for each module in series
  - The module model is mainly useful for remote diagnostic activities. Implementing this detailed information only through a local diagnostic connection (see 6.4) can save on bandwidth and data storage capacity.

6.3.2 Monitoring, control, and information exchange

For information interoperability, these communication capabilities should use a unified information model, and non-proprietary protocol encodings based on international standards or open industry specifications as described in 6.3.

The information to be exchanged falls into the following three categories:

- *Nameplate information:* This information is indicative of the as-built characteristics of the BMS and managed battery. This information may be read.
- *Monitoring information:* This information is indicative of the present operating conditions of the managed battery. This information may be read.

— *Management information:* This information is used to update functional and mode settings and the present operational constraints and interrupt constraints for each BMS function. This information may be read or written, given sufficient access privileges. The general information and control bus should not allow any changes to battery settings that could allow a violation of the SOA.

6.3.3 Nameplate information

Nameplate information should be available through the general information and control bus and include the information contained in Table 4. Note that the information recommended here can be distributed within multiple information models.

Table 4—Nameplate information

Parameter	Description
BMS Manufacturer	BMS Manufacturer
BMS Model	BMS Model
BMS Serial number	BMS Serial number
BMS Version	BMS Version
Battery Manufacturer(s)	Battery Manufacturer
Battery Model(s)	Battery Model
Battery Serial number(s)	Battery Serial number or numbers
Battery Type(s)	Battery Type. May be enumerated in some information models
Nameplate Charge Capacity	Nameplate charge capacity in amp-hours
Nameplate Energy Capacity	Nameplate energy capacity in dc watt-hours
Nameplate Max Charge Rate	Maximum rate of energy transfer into the storage device in dc watts
Nameplate Max Discharge Rate	Maximum rate of energy transfer out of the storage device in dc watts

In larger, multi-battery or multi-string BESSs, it can be difficult to clearly identify which batteries, strings, modules, and cells are reporting what information within an information model. For this reason, architectural information should be included to supplement nameplate information so that someone looking at the physical system can easily identify where data is coming from. While it is recommended in larger systems, architectural information can be superfluous in simple systems. Each BMS within a BESS should identify where it is located within the physical and/or network structure of the battery. The purpose of this information is to enable a user to connect the data communicated by a BMS with the physical and network location of the batteries being managed. For this reason, architectural information (as shown in Table 5) should be included to supplement nameplate information.

Table 5—Optional architecture information

Parameter	Description
Battery ID(s)	A list of identification numbers used to identify which battery or batteries within a BESS the BMS manages. For string, module, or cell level BMSs, this ID refers to the battery in which it is located.
String ID(s)	A list of identification numbers used to identify which string(s) within a battery the BMS manages. For module, or cell level BMSs, this ID refers to the string in which it is located.
Module ID(s)	A a list of identification numbers used to identify which module(s) within a string the BMS manages. For cell level BMSs, this ID refers to the module in which it is located.
Cell ID(s)	A a list of identification numbers used to identify which cell(s) or parallel assemblies within a module the BMS manages.
NOTE—The number of batteries, strings, modules, and cells can be calculated by what models are available on the communication bus and their length. However, the current information model does have an ID register for models 802 battery, 803 lithium-ion battery, or 806 flow battery. Hence, if a device has two or more batteries, it may not be clear which battery is providing what information.	

6.3.4 General battery monitoring information

The BMS should be capable of providing general monitoring information through the general information and control bus and should include the information contained in Table 6. Much of the information provided by a BMS is specific to the battery type but some information should be available from any battery under management.

Table 6—General battery monitoring information

Parameter	Description
State of Charge	State of charge, expressed as a percentage.
Battery Terminal Voltage	The external battery voltage or dc bus voltage.
Total DC Current	Total dc current flowing to/from the battery.
Total Power	Total power flowing to/from the battery bank.
Operational State	The operating state of the battery. May be enumerated in some information models. Should include: DISCONNECTED, CONNECTED, and FAULT.
Warning	Warning Code: Optionally includes specific information about any warning events including the ID(s), timestamp,[a] and description.
Fault	Fault Code: Optionally includes specific information about any fault events including the ID(s), timestamp,[a] and description.
Error	Error Code: optionally includes specific information about any error events including the ID(s), timestamp,[a] and description.

[a]The external systems such as the ESMS should apply the timestamp when they receive a warning, fault, or error from a BMS.

6.3.5 General battery management information

The general information bus in a BMS for batteries should include the information and control actions listed in Table 7 as applicable to its management. Management information may also include a control action to expand operational setting for extreme service conditions as discussed in 5.2.2.4.

Table 7—General battery management information

Parameter	Description
Connect	This control action should check if the associated battery state is within all operational constraints before closing the current-rated switch (see 4.2.8.3.1) to connect the battery to the PCS. This can require a pre-charge circuit (see 4.2.8.2).
Disconnect	This control action should open the associated current-rated switch (see 4.2.8.3.1).
Operational Maximum SOC	The maximum SOC that the battery is limited to during operation[O] (this is also called maximum reserve percent).
Operational Minimum SOC	The minimum SOC that the battery is limited to during operation[O] (this is also called minimum reserve percent).

6.3.6 Lithium-ion battery monitoring information

The general information bus in a BMS for lithium-ion batteries should include the information contained in Table 8, Table 9, Table 10, and Table 11 as applicable to its monitoring. This section supplements the general battery information provided in Clause 6.3.4.

Table 8—Lithium-ion battery monitoring information

Parameter	Description
String Count	Number of strings in the bank.
Connected String Count	Number of strings with switch closed.
Max Module Temperature	Maximum temperature for all modules in the bank.
Max Module Temperature ID(s)	The IDs of the string, module, or cell with maximum temperature.
Min Module Temperature	Minimum temperature for all modules in the bank.
Min Module Temperature ID(s)	The IDs of the string, module, or cell with minimum temperature.

Table 9—Lithium-ion string monitoring information

Parameter	Description
Module Count	Count of modules in the string.
String Status	Current status of the string. May be enumerated in some information models. Should include: DISCONECTED, CONNECTED, and FAULT.
String State-of-Charge	Battery string state of charge, expressed as a percentage.
String Voltage	String voltage measurement.
String Current	String current measurement.
Max Cell Voltage	Maximum voltage for all cells in the string.
Max Cell Voltage IDs	The IDs of the string, module, or cell with maximum temperature.
Min Cell Voltage	Minimum voltage for all cells in the string.
Min Cell Voltage IDs	The IDs of the string, module, or cell with minimum voltage.
Average Cell Voltage	Average voltage for all cells in the string.
Max Module Temperature	Maximum temperature for all modules in the bank.
Max Module Temperature IDs	Module with the maximum temperature.
Min Module Temperature	Minimum temperature for all modules in the bank.
Min Module Temperature IDs	Module with the minimum temperature.
Average Module Temperature	Average temperature for all modules in the bank.

Table 10—Lithium-ion module monitoring information

Parameter	Description
Module Cell Count	Count of all cells or parallel assemblies in the module.
Module Voltage	Voltage of the module.
Max Cell Voltage	Maximum cell voltage in module.
Max Cell Voltage ID	Cell or parallel assembly with the maximum voltage.
Min Cell Voltage	Minimum cell voltage in module.
Min Cell Voltage ID	Cell or parallel assembly with the minimum voltage.
Total Temperature Sensors	The number of temperature sensors in the battery module. When the module has one temperature sensor on each cell, this point can be omitted and the temperature sensor ID can be the same as the cell ID.
Max Module Temperature	Maximum temperature in module.
Max Module Temperature Sensor ID	Sensor with the maximum temperature.
Min Module Temperature	Minimum temperature in module.
Min Module Temperature Sensor ID	Sensor with the minimum temperature.
Average Module Temperature	Average temperature for all cells in the module.

Table 11—Lithium-ion cell monitoring information

Parameter	Description
Cell Voltage*	Cell or parallel assembly terminal voltage

*This is only recommended if there is sufficient bandwidth available and if analytics are being used to collect and process cell level data. Cell level voltage data can be useful in predictive maintenance programs.

6.3.7 Lithium-ion battery management information

The general information bus in a BMS for lithium-ion batteries may include the information in Table 12 as applicable to its management. If included, these parameters should only be writable through the diagnostic information and reconfiguration bus (see 6.4).

Table 12—Lithium-ion battery management information

Parameter	Description
Operational Maximum Cell Voltage	The maximum voltage that the battery cells are limited to during operation.[O]
Operational Minimum Cell Voltage	The minimum voltage that the battery cells are limited to during operation.[O]
Warning Maximum Cell Voltage	The voltage threshold above which high cell voltage warnings are issued.
Warning Minimum Cell Voltage	The voltage threshold below which low cell voltage warnings are issued.
Warning Cell Voltage Imbalance Threshold	The voltage imbalance threshold above which cell voltage imbalance warnings are issued.
Trip Maximum Cell Voltage	The voltage threshold above which high cell voltage faults are issued.[F]
Trip Minimum Cell Voltage	The voltage threshold below which low cell voltage faults are issued.[F]
Operational Maximum String Charge Current	The maximum charge current that the battery string is limited to during operation.[O]
Operational Maximum String Discharge Currnet	The maximum discharge current that the battery string is limited to during operation.[O]
Warning Maximum String Charge Current	The charge current threshold above which a high charge current warnings are issued.
Warning Maximum String Discharge Current	The discharge current threshold above which high discharge current warnings are issued.
Trip Maximum String Charge Current	The charge current threshold above which high charge current faults are issued.[F]
Trip Maximum String Discharge Current	The discharge current threshold above which high discharge current faults are issued.[F]
Warning Maximum SOC	The SOC threshold above which high SOC warnings are issued.
Warning Minimum SOC	The SOC threshold below which low SOC warnings are issued.
Trip Maximum SOC	The SOC threshold above which high SOC faults are issued.[F]
Trip Minimum SOC	The SOC threshold below which low SOC faults are issued.[F]
Operational Maximum Temperature	The maximum temperature that the battery is limited to during operation.[O]
Operational Minimum Temperature	The minimum temperature that the battery is limited to during operation.[O]
Warning Maximum Temperature	The temperature threshold above which high temperature warnings are issued.

Table continues

Table 12—Lithium-ion battery management information *(continued)*

Parameter	Description
Warning Minimum Temperature	The temperature threshold below which low temperature warnings are issued.
Trip Maximum Temperature	The temperature threshold above which high temperature faults are issued.[F]
Trip Minimum Temperature	The temperature threshold below which low temperature faults are issued.[F]

[F]This fault should trigger the BMS to activate its circuit interrupt device.
[O]Operational constraints are commonly not enforced by the BMS, but it is the device with sufficiently granular data to update operational constraints in real-time to prevent accelerated degradation. The ESMS, or other systems, can query the BMS to find the real-time operational constraints.

6.3.8 Flow battery monitoring information

The general information bus in a BMS for flow batteries should include the information contained in Table 13, Table 14, Table 15, Table 16, Table 17, and Table 18 as applicable to its monitoring. This section supplements the general battery information provided in 6.3.4.

Table 13—Flow battery monitoring information

Parameter	Description
String Count	Number of strings in the bank.
Connected String Count	Number of strings with switch closed.
Open Circuit Voltage	The open circuit voltage measured by a test cell.

Table 14—Flow battery string monitoring information

Parameter	Description
Module Count	Count of modules in the string.
String Status	Current status of the string. May be enumerated in some information models. Should include: DISCONECTED, CONNECTED, and FAULT.
String Voltage	String voltage measurement.
String Current	String current measurement.
Max Cell Voltage	Maximum voltage for all cells in the string.
Max Cell Voltage IDs	The IDs of the string, module, or cell with maximum temperature.
Min Cell Voltage	Minimum voltage for all cells in the string.
Min Cell Voltage IDs	The IDs of the string, module, or cell with minimum voltage.
Average Cell Voltage	Average voltage for all cells in the string.

Table 15—Flow stack monitoring information

Parameter	Description
Stack Cell Count	Count of all flow cells in the stack.
Stack Voltage	Voltage of the stack.
Max Cell Voltage	Maximum flow cell voltage in stack.
Max Cell Voltage ID	Flow cell with the maximum voltage.
Min Cell Voltage	Minimum flow cell voltage in stack.
Min Cell Voltage ID	Flow cell with the minimum voltage.
Average Cell Voltage	Average voltage for all cells in the stack.

Table 16—Flow cell monitoring information

Parameter	Description
Cell Voltage	The voltage of each flow cell.

Table 17—Electrolyte flow information

Parameter	Description
Electrolyte Pressure	Absolute or diferential pressure of the electrolyte.
Pump Status	Current status of the electrolyte pump(s). May be enumerated in some information models. Should include: OFF, RUNNING, and FAULT.

Table 18—Electrolyte monitoring information

Parameter	Description
Electrolyte Temperature	Temperatue of the electrolyte.
Electrolyte Tank Level	The level of fluid electrolyte in the electrolyte tank.

6.3.9 Flow battery management information

The general information bus in a BMS for flow batteries may include the information contained in Table 19 as applicable to its management. If included, these parameters should only be writeable through the diagnostic information and reconfiguration bus (see 6.4).

Table 19—Flow battery management information

Parameter	Description
Operational Maximum Cell Voltage	The maximum voltage that the battery cells are limited to during operation.[O]
Operational Minimum Cell Voltage	The minimum voltage that the battery cells are limited to during operation.[O]
Warning Maximum Cell Voltage	The voltage threshold above which high cell voltage warnings are issued
Warning Minimum Cell Voltage	The voltage threshold below which low cell voltage warnings are issued
Trip Maximum Cell Voltage	The voltage threshold above which high cell voltage faults are issued.[F]
Trip Minimum Cell Voltage	The voltage threshold below which low cell voltage faults are issued[F]
Operational Maximum String Charge Current	The maximum charge current that the battery string is limited to during operation.[O]
Operational Maximum String Discharge Currnet	The maximum discharge current that the battery string is limited to during operation.[O]
Warning High String Charge Current	The charge current threshold above which high charge current warnings are issued
Warning High String Discharge Current	The discharge current threshold above which high discharge current warnings are issued
Trip Maximum String Charge Current	The charge current threshold above which high charge current faults are issued.[F]
Trip Maximum String Discharge Current	The discharge current threshold above which high discharge current faults are issued.[F]
Warning Maximum SOC	The SOC threshold above which high SOC warnings are issued
Trip Maximum SOC	The SOC threshold above which high SOC faults are issued.[F]
Operational Maximum Pressure	The maximum pressure that the battery pumps are limited to during operation.[O]

Table continues

Table 19—Flow battery management information *(continued)*

Parameter	Description
Operational Maximum Electrolyte Temperature	The maximum temperautre that the battery electrolytes are limited to during operation.[O]
Operational Minimum Level	The minimum tank level that the battery electrolyte tanks are limited to during operation.[O]
Warning Maximum Pressure	The pressure threshold above which high pressure warnings are issued
Warning Minimum Pressure	The pressure threshold below which low pressure warnings are issued
Warning Minimum Electrolyte Level	The electrolyte tank level threshold below which low electrolyte tank level warnings are issued
Warning High Electrolyte Temperature	The temperature threshold above which high electrolyte temperature warnings are issued
Trip Maximum Pressure	The pressure threshold above which high pressure faults are issued[F]
Trip Minimum Pressure	The pressure threshold below which low pressure faults are issued[F]
Trip Minimum Electrolyte Level	The electrolyte tank level threshold below which low electrolyte tank level faults are issued.[F]
Trip Maximum Electrolyte Temperature	The temperature threshold above which high electrolyte temperature faults are issued.[F]

[F]This fault should trigger the BMS to activate its circuit interrupt device.
[O]Operational constraints are commonly not enforced by the BMS, but it is the device with sufficiently granular data to update operational constraints in real-time to prevent accelerated degradation. The ESMS, or other systems, can query the BMS to find the real-time operational constraints.

6.3.10 Sodium-β battery monitoring information

The general information bus in a BMS for sodium-β batteries should include the information contained in Table 20, Table 21, Table 22, and Table 23 as applicable to its monitoring. This section supplements the general battery information provided in 6.3.4.

Table 20—Sodium-β battery monitoring information

Parameter	Description
String Count	Number of strings in the bank.
Connected String Count	Number of strings with switch closed.
Max Module Temperature	Maximum temperature for all modules in the bank.
Max Module Temperature ID(s)	The IDs of the string, module, or cell with maximum temperature.
Min Module Temperature	Minimum temperature for all modules in the bank.
Min Module Temperature ID(s)	The IDs of the string, module, or cell with minimum temperature.

Table 21—Sodium-β string monitoring information

Parameter	Description
Module Count	Count of modules in the string.
String Status	Current status of the string. May be enumerated in some information models. Should include: DISCONECTED, CONNECTED, and FAULT.
String State-of-Charge	Battery string state of charge, expressed as a percentage.
String Voltage	String voltage measurement.
String Current	String current measurement.
Max Cell Voltage	Maximum voltage for all cells in the string.
Max Cell Voltage IDs	The IDs of the string, module, or cell with maximum temperature.
Min Cell Voltage	Minimum voltage for all cells in the string.

Table continues

Table 21—Sodium-β string monitoring information *(continued)*

Parameter	Description
Min Cell Voltage IDs	The IDs of the string, module, or cell with minimum voltage.
Average Cell Voltage	Average voltage for all cells in the string.
Max Module Temperature	Maximum temperature for all modules in the bank.
Max Module Temperature IDs	Module with the maximum temperature.
Min Module Temperature	Minimum temperature for all modules in the bank.
Min Module Temperature IDs	Module with the minimum temperature.
Average Module Temperature	Average temperature for all modules in the bank.

Table 22—Sodium-β module monitoring information

Parameter	Description
Module Cell Count	Count of all cells or parallel assemblies in the module.
Module Voltage	Voltage of the module.
Max Cell Voltage	Maximum cell voltage in module.
Max Cell Voltage ID	Cell or parallel assembly with the maximum voltage.
Min Cell Voltage	Minimum cell voltage in module.
Min Cell Voltage ID	Cell or parallel assembly with the minimum voltage.
Total Temperature Sensors	The number of temperature sensors in the battery module. When the module has one temperature sensor on each cell, this point can be omitted and the temperature sensor ID can be the same as the cell ID.
Max Module Temperature	Maximum temperature in module.
Max Module Temperature Sensor ID	Sensor with the maximum temperature.
Min Module Temperature	Minimum temperature in module.
Min Module Temperature Sensor ID	Sensor with the minimum temperature.
Average Module Temperature	Average temperature for all cells in the module.

Table 23—Sodium-β cell monitoring information

Parameter	Description
Cell Voltage	Cell or parallel assembly terminal voltage.

6.3.11 Sodium-β battery management information

The general information bus in a BMS for sodium-β batteries may include the information contained in Table 24 as applicable to its management. If included, these parameters should only be writable through the diagnostic information and reconfiguration bus (see 6.4).

Table 24—Sodium-β management information

Parameter	Description
Operational Maximum Cell Voltage	The maximum voltage that the battery cells are limited to during operation.[O]
Operational Minimum Cell Voltage	The minimum voltage that the battery cells are limited to during operation.[O]
Warning Maximum Cell Voltage	The voltage threshold above which high cell voltage warnings are issued.
Warning Minimum Cell Voltage	The voltage threshold below which low cell voltage warnings are issued.

Table continues

Table 24—Sodium-β management information *(continued)*

Parameter	Description
Warning Cell Voltage Imbalance Threshold	The voltage imbalance threshold above which cell voltage imbalance warnings are issued.
Trip Maximum Cell Voltage	The voltage threshold above which high cell voltage faults are issued.[F]
Trip Minimum Cell Voltage	The voltage threshold below which low cell voltage faults are issued.[F]
Operational Maximum String Charge Current	The maximum charge current that the battery string is limited to during operation.[O]
Operational Maximum String Discharge Currnet	The maximum discharge current that the battery string is limited to during operation.[O]
Warning Maximum String Charge Current	The charge current threshold above which high charge current warnings are issued.
Warning Maximum String Discharge Current	The discharge current threshold above which high discharge current warnings are issued.
Trip Maximum String Charge Current	The charge current threshold above which high charge current faults are issued.[F]
Trip Maximum String Discharge Current	The discharge current threshold above which high discharge current faults are issued.[F]
Warning Maximum SOC	The SOC threshold above which high SOC warnings are issued.
Warning Minimum SOC	The SOC threshold below which low SOC warnings are issued.
Trip Maximum SOC	The SOC threshold above which high SOC faults are issued.[F]
Trip Minimum SOC	The SOC threshold below which low SOC faults are issued.[F]
Operational Maximum Temperature	The maximum temperature that the battery is limited to during operation.[O]
Operational Minimum Temperature	The minimum temperature that the battery is are limited to during operation.[O]
Warning Maximum Temperature	The temperature threshold above which high temperature warnings are issued.
Warning Minimum Temperature	The temperature threshold below which low temperature warnings are issued.
Trip Maximum Temperature	The temperature threshold above which high temperature faults are issued.[F]
Trip Minimum Temperature	The temperature threshold below which low temperature faults are issued.[F]

[F]This fault should trigger the BMS to activate its circuit interrupt device.
[O]Operational constraints are commonly not enforced by the BMS, but it is the device with sufficiently granular data to update operational constraints in real-time to prevent accelerated degradation. The ESMS, or other systems, can query the BMS to find the real-time operational constraints.

6.4 Diagnostic information and reconfiguration bus

6.4.1 General

Clause 6.4 describes the functionality of a BMS diagnostic information and reconfiguration bus. This can be one or more dedicated ports or communications buses. The functionality can be divided into a diagnostic bus, used to access detailed data from the BMS, and a reconfiguration bus, which is an optional feature to enable BMS function and communications settings to be changed in the field. Together, these features are used in troubleshooting the BMS or in troubleshooting the battery using the BMS.

A diagnostic bus can be used by battery technicians to access detailed information about the status and historical operation of a battery. Importantly, a diagnostic bus does not need to be interoperable as it is not always intended to be accessed by customers or third parties. This lack of interoperability contrasts its functionality with the general information and control bus described in 6.3 which should connect to and work with systems developed by other manufacturers. A diagnostic bus is designed to provide much richer data to a technician with an appropriate level of access.

6.4.2 Diagnostic information model

The data and data format for diagnostic information is a design decision made by a BMS manufacturer. More data can, in general, allow for more and better analytics but can increase the cost of a design by increasing requirements for sensors, memory, and computation.

An on-board record of errors and faults should be retained for the life of the battery and accessible via the BMS's diagnostic bus. A record of warnings should be retained for as long as practical, recommended minimum record of 90 d, with rolling deletion of the oldest warnings as necessary to preserve memory. A code, and the index for the cell or module it applies to, can be represented with a single precision variable (4 B) with the timestamp it occurred at taking another single precision variable. Annex D includes a list of example descriptive warnings, faults, and errors that provide information to a technician sufficient for debugging. At a minimum, the record should include the code, timestamp, and specific identifiers for the source. The code is used with a lookup table to provide the name of the error, fault, or warning, which can be consulted in the BMS's documentation. The name should correspond to a longer description of the error, fault, and warning in the BMS's documentation that identifies why the error may have occurred and any corrective actions that a technician should employ.

An on-board record of local/remote access should be retained for the life of the battery and should include their IP address and user information.

6.4.3 Internal data historian aggregation/compression

One of the challenges for managing BESS data is that the number, frequency, and precision of all the potentially relevant data are such that data storage and processing are expensive and time consuming. It is often infeasible to record all battery data for all time. For this reason, Table 25 provides a list of recommended on-board data retention periods and minimum sample rates for steady state battery data to aid in maintenance and, should the need arise, post incident analysis. These limits should not be applied to cloud-based or other mass storage of battery data.

Table 25—Recommended steady state data retention periods and sample rates

Data name	Retention period (recommended minimum)	Sample period (recommended minimum)	Estimated on-board memory (based on double precision variables)
Cell/module voltages	30 d	1 sample/min	345.6 KB per cell (1036.8 KB with short-board[b] method)
String voltages	30 d	1 sample/min	345.6 KB
Cell/module/ambient temperatures	30 d	1 sample/min	345.6 KB per sensor (1036.8 KB with short-board[b] method)
Cell ohmic values (if applicable to battery type[a])	For the life of the battery	1 sample/day (at the same SOC and T if possible)	29.2 KB per 10 years per cell (87.6 per 10 years with short-board[b] method)
Current	30 d	1 sample/min	345.6 KB per string
Power	30 d	1 sample/min	345.6 KB
Aggregate SOC	30 d	1 sample/min	345.6 KB
Aggregate SOH	For the life of the battery	1 sample/day	29.2 KB per 10 years

[a]Lithium-ion battery systems and many other battery systems normally do not record cell ohmic values.
[b]For purposes of data retention efficiency, the "short-board" method can be used. This refers to recording only three values per string: max cell value, average cell value, and minimum cell value. If this method is used, then the number of series cells/string should be specified in the data or documentation. Further, integer values corresponding to the cells that the maximum value and minimum values were recorded from should be recorded along with each measurement.

To save memory, the BMS historian may be configured to record only changes in values, or changes in the trends that values are taking, rather than recording values on a specified schedule. This can be especially effective for batteries used in standby applications because values are static for long periods. It can be difficult to calculate the memory required for this configuration because it depends on how often the battery is used. It is recommended that a regular sample period be used for calculating minimum memory requirements.

There is sometimes a need for all data produced by the BMS to be recorded, such as during certain performance tests. Generally, these data are recorded separately from the BMS historian in a discrete memory location or even in an external device such as the ESMS. The external location can be removable storage (e.g., an SD card) or a technician's laptop connected to the BMS's diagnostic bus (see 6.4). If a high sample rate recording feature is used, the documentation should specify how much time or memory is available for it and should allow the device owner to clear specific records or all records.

6.4.4 Reconfiguration

BMSs that can protect multiple battery types in multiple applications should include a reconfiguration feature. Reconfiguration enables updating the BMS functions that are enabled along with all relevant settings and parameters. BMS reconfiguration should be performed only by a technician with appropriate access (see 6.5.3).

6.5 Cybersecurity

6.5.1 General

The goals of cybersecurity are to protect the confidentiality, integrity, availability, and non-repudiation of information. Confidentiality refers to information only being known by those people and systems who are authorized. Integrity refers to the authenticity of information and its source. Availability is the ability of the intended recipients to make use of the information. Lastly, non-repudiation is the ability to accept information when the communication is authorized or legitimate. IEEE Std 1547.3-2023 [B21] provides detailed recommendations for cybersecurity of DER. IEEE Std 1547.3-2023 [B21] emphasizes the importance of implementing cybersecurity within and across organizations and networks. Network cybersecurity is normally implemented via a gateway that also converts from the Modbus communication within the BESS to the SCADA protocol implemented by the local utility (often DNP3). Such gateways are beyond the scope of this document. The role of the BMS in cybersecurity is to have specific features that enable cybersecurity at the network and organizational levels. This subclause provides recommendations for BMS features that support this purpose.

6.5.2 Physical security

Physical security can be a critical element of cybersecurity. Physical access to an installed BMS, as well as the network it is connected to, should be controlled by barriers, locks, or other access control measures, as follows:

- Unused external communications ports should be disabled in software or phisically blocked when possible.
- Unused communication connections including wireless (e.g., IEEE 802.15.4 (BlueTooth) and IEEE 802.11 (Wi-Fi)) on installed equipment should be removed or disabled.
- Modifications to settings through physical equipment panels should be monitored and logged.
- Where it is reasonable to do so, the operator should be notified of battery room or battery system door opening.

6.5.3 Access control

6.5.3.1 General

This subclause provides recommendations for access control for users, as follows:

- Authentication – All electronic access to the BMS, whether locally through a control panel or diagnostic port, or remotely through communications media, should be protected with an authentication mechanism that identifies a user with a unique user identification (ID) and password combination.
- User authorization – Users should be assigned permissions to access data, services, resources, or objects granted by the security policy. These permissions should also be constrained to one or more of the following: viewing (seeing), reading (downloading), writing (uploading), issuing control commands, creating new items, or deleting items.
- User accountability and non-repudiation – User actions should be logged so events can be traced, time-synchronized with other events, and/or audited. The BMS may be configured to discretely notify authorized monitors of remote connections, whether they are authorized or not. This can give monitors a chance to verify the authorization of the remote access.
- User-created passwords should follow a set of rules that should be adhered to in the creation of each password. Passwords should be at least eight characters in length and should be case sensitive. It should not use common dictionary words and/or consecutive and repeatable characters. When encoding passwords in plain text, the password characters should contain the following:
  - At least one uppercase and one lowercase letter
  - At least one number
  - At least one non-alphanumeric character (e.g., @, %, &, *)
- Any attempt to create a password that violates these rules should be captured at the time of attempted creation, and the user should be notified and prompted to choose another password that conforms to the rules.
- Access failures should support adjustable account lockout thresholds and durations.
- Passwords and other security tokens should never be displayed through any means, including local display panel, configuration software (local or remote; offline or online), web browser, and terminal access.
- User access capabilities should include a timeout feature that automatically logs out a user after a period of user inactivity.

6.5.3.2 Access management

This subclause provides the following recommendations for BMS access management:

- It is recommended that a unique randomized password be provided as the initial password for each deployed BMS and that it be printed on the device itself. Resetting the BMS to factory defaults may reset the access password to this initial state.
- Initial passwords should be required to be changed upon installation or any change of ownership or location of BMS.
- Multiple users and multiple software applications with different access permissions should be supported by the BMS.
- Secure interfaces should provide an open and documented method for adding and updating user accounts, passwords, and assignment to roles.
- All access changes should be logged.

6.5.3.3 Role-based access control (RBAC)

This subclause provides recommendations for RBAC, as follows:

- RBAC should be supported by the BMS.
- Users should be assigned to one or more roles which have the permissions necessary for the user to perform their tasks.
- When responding to requests for access, the BMS should verify that the requests are permitted for the roles of the person or device making the requests. The requests should be rejected if the roles do not have the correct permissions. Rejected requests should be logged.
- The BMS should have the capability of defining multiple user-defined roles. Each role should have the capability of having any combination of rights, including the following:
  - Reading BMS nameplate or configuration information, measurement data (voltage, current, power, energy, status, alarms, etc.), and control mode settings.
  - Writing control mode settings that alter the operational characteristics of the BMS.
  - Additional functionality should be documented.
- The BMS should support the "push" RBAC model and accept valid role tokens.
- A role should be assignable in the BMS using an IEC 62351-8 Profile A token. Additional methods of assigning roles to subjects/users should be permitted.
- All RBAC changes should be logged.

6.5.4 Software update management

Software/firmware updates can enable additional features and algorithmic improvements in deployed systems. Updates can also enable the correction of software bugs and cyber-vulnerabilities. However, the software update process can also itself be a cyber-vulnerability and so care should be taken in how updates are performed, as follows:

- The BMS may support the ability for remote updates.
- The BMS may support the ability to be configured for and disable automated updates.
- The BMS should verify the authenticity and integrity of software updates.

  NOTE—A common integrity control is the use of a digital signature. A digital signature is a string of data accompanying the update, derived by encrypting the update itself, that can be checked by the device before it applies the update. If the update has been modified or corrupted in transit, the signature will not match the update and it can be rejected. An alternative integrity control is to require physical access to the BMS to update its software through a physical update switch on the device, requiring a dongle to be inserted, or similar methods.
- The BMS should be commissioned with the most recent firmware version.
- The BMS supplier should provide a policy on product support including firmware updates.
- The BMS supplier should inform integrators, aggregators, and owners in a recognizable and apparent manner (e.g., on a website) that a security update is available.
- The BMS supplier should provide information on applicability, compatibility, and risks mitigated by the update.
- The software update process should be designed to minimize the duration battery management functions are not provided. The BMS supplier should notify the aggregator, owner, or operator when the application of a software update will disrupt battery management functions.

— The BMS supplier should provide, in an accessible way that is clear and transparent to the aggregator, owner, or operator, the defined device support period.

— The BMS supplier should publish a list of all updates and their approval status.

NOTE—UL 5500 Standard for Safety for Remote Software Updates [B56] contains additional information.

6.5.5 Data security

6.5.5.1 Security for data-at-rest

This subclause provides recommendations for the security of stored data, such as the data logged on the BMS itself, as follows:

— Authentication methods should be used to authorize any viewing, read, write, create, or delete access to stored data.

— On removing, disposing, or repurposing devices, a sanitization process should be used to remove any confidential data at rest on the BMS, such as a factory reset option.

6.5.5.2 Security for data-in-transit

This subclause provides recommendations for the BMS to support the security of data-in-transit, as follows:

— The BMS should support one or more communication protocols with cybersecurity features that can be implemented on a network. Common protocols include IEC 61850 [B15], IEEE Std 1815™ (DNP3) [B28], IEEE Std 2030.5™ [B30], and SunSpec Modbus [B36], SunSpec Information Model Reference [B50], SunSpec Information Models [B51], and SunSpec Technology Overview [B52].

  NOTE—CANbus (ISO 11898-2:2016 [B32]) and Modbus serial do not natively support authentication. Security features can be difficult to implement on CANbus, but a few methods are described in Groza, B. and P. Murvay [B8]. Modbus TCP supports authentication via a Transport Layer Security (TLS) wrapper.

— TLS v1.3 should be supported where practical, as specified in IEC 62351-3 [B16], recognizing that some installations may still need to use TLS 1.2.

Annex A

(normative)

BMS ESMS overlap

Throughout this document the BMS is considered to be a separate device from the ESMS. However, this is not always the case. In many fielded systems the ESMS performs some battery management functions or the BMS performs some energy management functions. A simple example of this is a function within a BMS that controls a charging profile to minimize the customer's energy costs. This is an energy management function performed by the same device that enforces operational and interrupt constraints of the battery. Any energy management functions implemented within a BMS should be given a lower priority in software than all BMS functions. Energy management functions are outside of the scope of this document.

Implementing BMS functions in the ESMS is not recommended. An example of a BMS function that is sometimes implemented in the ESMS is a current management function to extend the life of the battery by reducing the maximum power requested from the batteries at high temperatures. There are several problems with this. First, the ESMS implementing BMS functions would rely on data collected from a BMS. Second, changes to the energy management algorithm could disrupt the protective function of the operational constraint leading to a reduced battery lifetime. Energy management systems also often act as a gateway device to external networks and so there are cybersecurity implications of implementing protection functions on a device that is more vulnerable to attack.

Annex B

(informative)

Balancing circuit calculations

A BC helps correct unbalanced states of charge in strings of battery cells or modules by adjusting cell voltages to match. Due to normal manufacturing tolerances, battery cells within a system can have differing characteristics (efficiency, capacity, rate of self-discharge, etc.). These differences can, over time and use, cause the cells' SOCs to drift apart. If left uncorrected, variances in cell SOC causes operational issues and limits system performance as shown in Figure B.1. A BC can be configured to operate in three different ways:

— Removing energy from high SOC cells.

— Supplying energy to low SOC cells.

— Shunting energy from high SOC cells to low SOC cells.

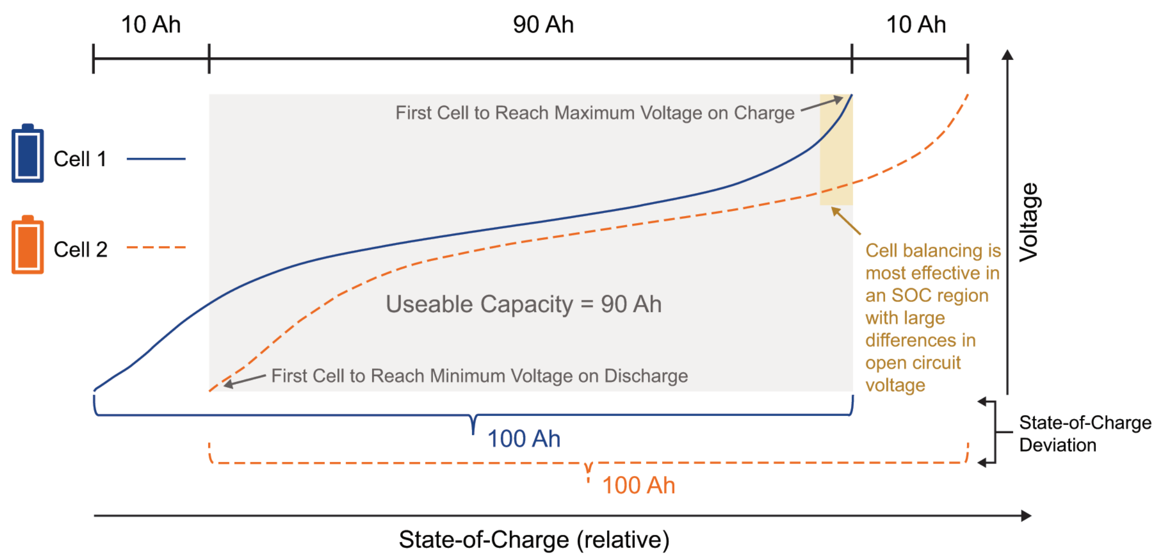

Figure B.1—Illustration of battery string performance limits from cell SOC variance

Removing energy from high SOC cells is done by selectively connecting cells to shunt resistors or other passive circuit elements, allowing excess energy to be dissipated as heat (referred to as passive balancing). Supplying extra energy to low SOC cells can be done by selectively connecting cells to an external power supply (referred to as power supply balancing). Both can be accomplished simultaneously by selectively connecting high SOC cells in parallel with low SOC cells through power electronics that control the magnitude of current flowing between them (referred to as active balancing).

When used during operation, BCs impact the accuracy of voltage measurement for participating cells. This is a result of the cell terminal voltage changing because of the small charge or discharge but also because, depending on the circuit architecture, the balancing current can pass through the same wires used by the BMS for voltage sensing.

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. A BMS can be configured to implement the operational requirements automatically on a specified schedule or under a specified set of conditions (e.g., implement a balancing cycle between midnight and 5:00am every Sunday if the system is not otherwise in use). For battery types that have a flat voltage curve except at SOC extrema (e.g., lithium-iron-phosphate), it may be useful to configure the BMS to periodically request that the PCS charge or discharge the battery such that the BMS is able to identify the high and low SOC cells or modules to implement balancing.

It is difficult to calculate precisely how much balancing is needed in design as it is a function of the variability in cell self-discharge, which can vary over life and between manufacturing runs. The maximum power that a BMS can use to balance the energy in cells is limited by its internal circuitry and potentially by its ability to dissipate heat. Oversizing the BC can be costly in terms of circuit components, while undersizing it extends balancing time and could lead to either a steady loss of the string's usable capacity or a lower availability factor for the battery because of the need for outages to allow more time for the BC work.

The maximum sustained balancing power is the power that the BMS can remove from high voltage cells, inject into low voltage cells, or both averaged over a period of time that accounts for any on/off cycling required. For example, a BC with 50 cell connections, for 3.6 V cells, has a maximum balancing current of 200 mA, but if its architecture has one resistor for every 10 cells that it switches between during operation, then the maximum sustained balancing power would be 72 mW per cell (3.6 V × 200 mA / 10 cells) or 3.6 W total (72 mW × 50 cell connections). The maximum sustained balancing power rating, along with the balancing type and architecture, allows a system designer to calculate the maximum voltage imbalance that the BMS is able to correct over time.

Voltage imbalance is a measure of the inequalities in voltage between cells in a battery and is calculated differently based on the type of BC. Figure B.2 shows an illustration of how the magnitude of balancing required depends on how the BC acts. The three plots show the same distribution of 10 cell voltages at rest. The green band shows the circuit's voltage tolerance band. The top plot shows how the circuit can be brought into a state of balance by reducing the voltage of three cells. The middle plot shows how the same circuit would need to charge seven cells to be brought into a state of balance. The bottom plot shows how a circuit that moves or shunts energy from high cells to low cells would be able to be brought into balance by removing energy from two cells and adding it to one cell. Putting the whole string on a float charge can allow some BCs to shunt charge current around high voltage cells such that they do not receive as much charge as low voltage cells. This configuration would measure voltage imbalance identically to the "removing energy from high voltage cells" case. The important factor for the voltage imbalance is which cells within the string the circuit can isolate to adjust their charge: high voltage cells, low voltage cells, or both.

Another useful distinction is between passive and active cell balancing. Passive cell balancing is the dissipation of energy from cells into passive circuit components while active cell balancing involves redistribution of energy between cells. Passive balancing can be achieved through many circuit designs using Zener diodes, voltage comparators, or even simple electrolysis, which is commonly used in aqueous battery chemistries to balance strings of cells. Active BCs control metal-oxide-semiconductor field-effect transistors (MOSFET), or transistor switches to transfer energy from higher voltage cells to lower voltage cells.

If the circuit elements are undersized, then the cell voltages can drift apart during operation and the battery may need to undergo regular outages to allow time for the BC to bring cells back within the voltage tolerance window, or the useable capacity could steadily decline. Following is a set of definitions and calculations that allow a designer to determine if a BC is powerful enough to keep a given battery's useable capacity stable:

— *Voltage imbalance:* The difference between the open-circuit-voltage (V) of a cell or parallel assembly and the closest edge of the voltage tolerance window.
— *Energy imbalance:* The difference in energy (Wh) of a cell or parallel assembly to the state of energy that would place it within the voltage tolerance window. Can be estimated by dividing the voltage

imbalance by the derivative of the average open-circuit-voltage function, with respect to state-of-energy, evaluated at at the string's present state-of-energy.

— *Total energy imbalance:* The sum of energy imbalance for all cells in a BC.

— *Total energy imbalance rate:* The rate of change in the total energy imbalance measured in Wh per month.

— *BMS balancing power:* The maximum power that the BMS can remove or apply to balance a cell's charge.

— *BMS total balancing power:* The maximum power that the BMS can remove or apply to balance all cells in its BC. If a circuit is designed to balance just a few cells at a time, this is often much less than the BMS balancing power multiplied by the number of cells in a balancing group.

— *BMS total sustained balancing power:* The maximum power that the BMS can remove or apply to balance all cells in its BC, averaged over a long duration, measured in Wh per month.

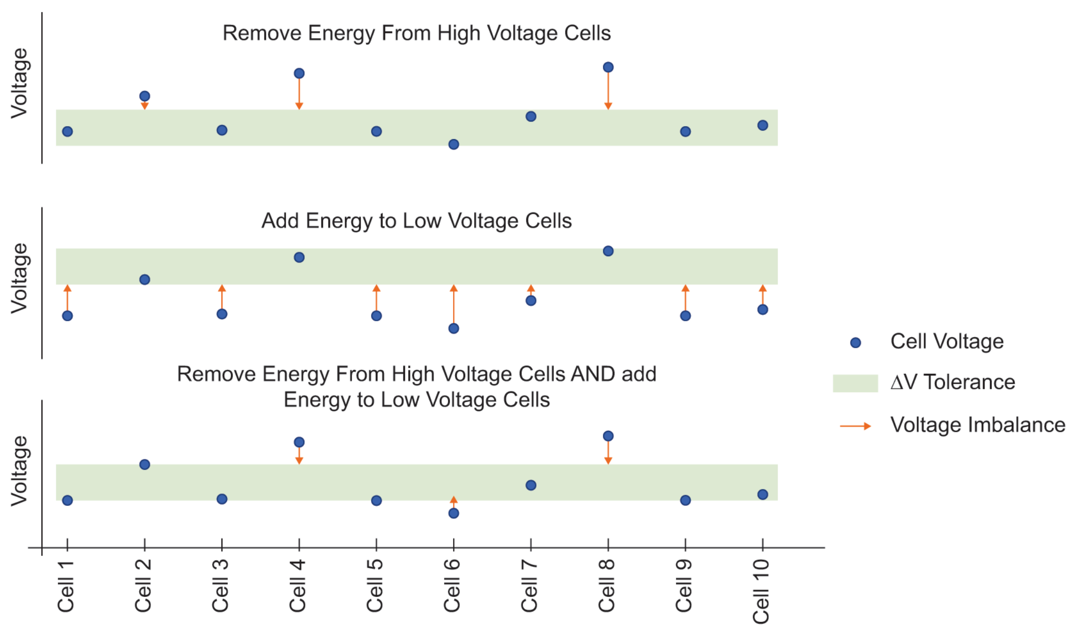

Figure B.2—Illustration of how Imbalance Magnitude depends on Balancing Type

Annex C

(informative)

Digital twins

Frequently, cybersecurity measures (see 6.5) prohibit remote data access to a physical BMS, because the provision of such access would render the network on which the BMS resides vulnerable to malicious actors. Furthermore, BMS hardware typically provides for only limited local data storage in the form of “black box” data (see 6.4.3). These limitations can be overcome through the implementation of digital twins.

In the context of this document, a digital twin is a virtual representation of a physical BMS. Also known as a digital shadow or device shadow, a digital twin is formed through the secure one-way transmission of BMS data to a cloud-based server, where it can be accessed without creating cybersecurity concerns for the physical device. Not only can the digital twin be updated in near real time, but it can also store historical data, so data access is less constrained through both location and time than with the physical counterpart.

Digital twins allow manufacturers to offer additional services, such as remote monitoring, prognostics, troubleshooting, and analysis of operational data to identify conditions that are potentially life-shortening for the battery. Historical data can also provide a convenient means of verifying warranty compliance.

Annex D

(informative)

Example error, warning, and fault codes and descriptions

Example error, warning, and fault codes and descriptions

Code	Description	Closest* SunSpec Information Model and Event Code [B51]
Error: Cell voltage is n/a, String [#], Cell [#], Recorded at [timestamp**]	ERROR: This error occurs when the BMS records a cell voltage that implies something has gone wrong in the measurement itself (e.g., 0 V, or 99 999 V). The BMS has actuated the circuit interrupt device in string # [#], removing it from service. This error could be caused by an intermittent short or open circuit in measurement wiring.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 0 Event Name: COMMUNICATION_ERROR
Error: String current is n/a, String [#], Recorded at [timestamp**]	ERROR: This error occurs when the BMS records a string current that implies something has gone wrong in the measurement itself (e.g., 99 999 A). The BMS has actuated the circuit interrupt device in string # [#], removing it from service. This error could be caused by an intermittent short circuit in measurement wiring. In Hall-effect type current sensors, this error could be caused by a hardware fault in the sensor.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 0 Event Name: COMMUNICATION_ERROR
Error: Sensor Temperature is n/a, String [#], Sensor [#], Recorded at [timestamp**]	ERROR: This error occurs when the BMS records a temperature that implies something has gone wrong in the measurement itself (e.g., −99 999 °C or 99 999 °C). The BMS has actuated the circuit interrupt device in string # [#], removing it from service. This error could be caused by an intermittent short or open circuit in measurement wiring.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 0 Event Name: COMMUNICATION_ERROR
Error: Cell SOC is n/a, String [#], Cell [#], Recorded at [timestamp**]	ERROR: This error occurs when the BMS records a cell SOC that implies something has gone wrong in the measurement or calculation itself (e.g., 99 999%). The BMS has actuated the circuit interrupt device in string # [#], removing it from service. This error could be caused by an error in voltage current or temperature measurements, or by a communication error in transmitting those data from a remote measurement device to the BMS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 0 Event Name: COMMUNICATION_ERROR
Warning: BMS Warning for: Cell Voltage [V] > High Cell Voltage Warning [V], String [#], Cell [#], Recorded at [timestamp**]	Warning, the BMS has detected that the VOLTAGE of cell # [#] in string # [#] has exceeded the High Cell Voltage Warning threshold. The cell voltage was measured to be [V] volts and the High Cell Voltage Warning threshold is currently set at [V] volts. This condition could lead to the accelerated degradation in cell # [#] if not corrected. This could be caused by the operational constraints on voltage or current being improperly configured in the PCS, or by insufficient balancing of charge between cells in string # [#].	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 10 Event Name: OVER_VOLT_WARNING
Warning: BMS Warning for: Cell Voltage [V] < Low Cell Voltage Warning [V], String [#], Cell [#], Recorded at [timestamp**]	Warning, the BMS has detected that the VOLTAGE of cell # [#] in string # [#] has fallen below the Low Cell Voltage Warning threshold. The cell voltage was measured to be [V] volts and the Low Cell Voltage Warning threshold is currently set at [V] volts. This condition could lead to the accelerated degradation in cell # [#] if not corrected. This could be caused by the operational constraints on voltage or current being improperly configured in the PCS, by insufficient balancing of charge between cells in string # [#], or it could be an early sign of cell failure.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 12 Event Name: UNDER_VOLT_WARNING

Table continues

Example error, warning, and fault codes and descriptions *(continued)*

Code	Description	Closest* SunSpec Information Model and Event Code [B51]
Warning: BMS Warning for: High Voltage Imbalance [V] > Cell Voltage Imbalance Warning [V], String [#], Recorded at [timestamp**]	Warning, the BMS has detected that the VOLTAGE IMBALANCE of string # [#] has exceeded the Cell Voltage Imbalance Warning threshold. The string voltage imbalance was measured to be [V] volts and the Cell Voltage Imbalance Warning threshold is currently set at [V] volts. This could be caused by insufficient balancing of charge between cells in string # [#], or it could be an early sign of cell failure.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 17 Event Name: VOLTAGE_ IMBALANCE _WARNING
Warning: BMS Warning for: Discharge Current [I] > High Discharge Current Warning [I], String [#], Recorded at [timestamp**]	Warning, the BMS has detected that the CURRENT of string # [#] has exceeded the High Discharge Current Warning threshold. The string current was measured to be [I] amps and the High Discharge Current Warning threshold is currently set at [I] amps. This condition could lead to excess heating and accelerated degradation in string # [#] if left unaddressed. This could be caused the operational constraints on current being improperly configured in the PCS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 8 Event Name: OVER_ DISCHARGE _CURRENT_WARNING
Warning: BMS Warning for: Charge Current [I] > High Charge Current Warning [I], String [#], Recorded at [timestamp**]	Warning, the BMS has detected that the CURRENT of string # [#] has exceeded the High Charge Current Warning threshold. The string current was measured to be [I] amps and the High Charge Current Warning threshold is currently set at [I] amps. This condition could lead to excess heating and accelerated degradation in string # [#] if left unaddressed. This could be caused the operational constraints on current being improperly configured in the PCS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 6 Event Name: OVER_CHARGE _CURRENT_WARNING
Warning: BMS Warning for: Sensor Temp [T] > High Temp Warning [T], String [#], Sensor [#], Recorded at [timestamp**]	Warning, the BMS has detected that the TEMPERATURE measured by sensor # [#] in string # [#] has exceeded the High Temperature Warning threshold. The temperature was measured to be [T] degrees C and the High Temperature Warning threshold is currently set at [T] degrees C. This condition could lead to the accelerated degradation in string # [#] if not corrected. This could be caused by insufficient cooling of the battery's environment or by an obstruction of airflow to a part of the battery.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 2 Event Name: OVER_ TEMP_WARNING
Warning: BMS Warning for: Sensor Temp [T] < Low Temp Warning [T], String [#], Sensor [#], Recorded at [timestamp**]	Warning, the BMS has detected that the TEMPERATURE measured by sensor # [#] in string # [#] has fallen below the Low Temperature Warning threshold. The temperature was measured to be [T] degrees C and the Low Temperature Warning threshold is currently set at [T] degrees C. This condition could lead to the accelerated degradation in string # [#] if not corrected. This could be caused by insufficient heating of the battery's environment or by an obstruction of airflow to a part of the battery.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 4 Event Name: UNDER_ TEMP_WARNING
Warning: Temperature Imbalance [T] > Temperature Imbalance Warning [T], String [#], Cell [#], Recorded at [timestamp**]	Warning, the BMS has detected that the TEMPERATURE IMBALANCE measured in string # [#] has exceeded the Temperature Imbalance Warning threshold. The temperature imbalance was measured to be [T] degrees C and the Temperature Imbalance Warning threshold is currently set at [T] degrees C. This condition could lead to the uneven degradation in string # [#] if not corrected. This could be caused by insufficient air circulation within the battery's environment or by an obstruction of airflow to a part of the battery.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 19 Event Name: TEMPERATURE _IMBALANCE_WARNING

Table continues

Example error, warning, and fault codes and descriptions *(continued)*

Code	Description	Closest* SunSpec Information Model and Event Code [B51]
Warning: BMS Warning for: SOC [%] > High SOC Warning [%], String/Module/Cell [#], Recorded at [timestamp**]	Warning, the BMS has detected that the STATE OF CHARGE estimated in string # [#] has exceeded the High SOC Warning threshold. The SOC was measured to be [%]% and the High SOC Warning threshold is currently set at [%]%. This condition could lead to the accelerated degradation in string # [#] if not corrected. This could be caused the operational constraints on SOC being improperly configured in the charger or ESMS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 16 Event Name: OVER_SOC _MAX_WARNING
Warning: BMS Warning for: SOC [%] < Low SOC Warning [%], String/Module/Cell [#], Recorded at [timestamp**]	Warning, the BMS has detected that the STATE OF CHARGE estimated in string # [#] has fallen below the Low SOC Warning threshold. The SOC was measured to be [%]% and the Low SOC Warning threshold is currently set at [%]%. This condition could lead to the accelerated degradation in string # [#] if not corrected. In grid supporting applications, this could be caused the operational constraints on SOC being improperly configured in the ESMS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 14 Event Name: UNDER_SOC _MIN_WARNING
Fault: BMS Trip for: Cell Voltage [V] > Trip Max Cell Voltage [V], String [#], Cell [#], Recorded at [timestamp**]	FAULT: The BMS has detected that the VOLTAGE of cell # [#] in string # [#] has exceeded the Trip Max Cell Voltage threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The cell voltage was measured to be [V] volts and the Trip Max Cell Voltage threshold is currently set at [V] volts. This could be caused by the operational constraints on voltage or current being improperly configured in the PCS, or by insufficient balancing of charge between cells in string # [#].	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 9 Event Name: OVER_VOLT_ALARM
Fault: BMS Trip for: Cell Voltage [V] < Trip Min Cell Voltage [V], String [#], Cell [#], Recorded at [timestamp**]	FAULT: The BMS has detected that the VOLTAGE of cell # [#] in string # [#] has fallen below the Trip Min Cell Voltage threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The cell voltage was measured to be [V] volts and the Trip Min Cell Voltage threshold is currently set at [V] volts. This could be caused by the operational constraints on voltage or current being improperly configured in the PCS, by insufficient balancing of charge between cells in string # [#], or it could be a sign of cell failure.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 11 Event Name: UNDER_VOLT_ALARM
Fault: BMS Trip for Discharge Current [I] > Trip Max Discharge Current [I], String [#], Recorded at [timestamp**]	FAULT: The BMS has detected that the CURRENT of in string # [#] has exceeded the Trip Max Discharge Current threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The string current was measured to be [I] amps and the Trip Max Discharge Current threshold is currently set at [I] amps. This could be caused by the operational constraints on voltage or current being improperly configured in the PCS, or a high impedance fault on the dc bus that did not activate the overcurrent protection.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 7 Event Name: OVER_DISCHARGE _CURRENT_ALARM
Fault: BMS Trip for Charge Current [I] > Trip Max Charge Current [I], String [#], Recorded at [timestamp**]	FAULT: The BMS has detected that the CURRENT of in string # [#] has exceeded the Trip Max Charge Current threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The string current was measured to be [I] amps and the Trip Max Charge Current threshold is currently set at [I] amps. This could be caused by the operational constraints on voltage or current being improperly configured in the PCS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 5 Event Name: OVER_CHARGE _CURRENT_ALARM

Table continues

Example error, warning, and fault codes and descriptions *(continued)*

Code	Description	Closest* SunSpec Information Model and Event Code [B51]
Fault: BMS Trip for: Sensor Temp [T] > Trip Max Temp [T], String [#], Sensor [#], Recorded at [timestamp]	FAULT: The BMS has detected that the TEMPERATURE measured by sensor # [#] in string # [#] has exceeded the Trip Max Temperature threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The temperature was measured to be [T] degrees C and the Trip Max Temperature threshold is currently set at [T] degrees C. This could be caused by a high-rate charge or discharge event exceeding battery cooling limits, insufficient cooling of the battery's environment, by an obstruction of airflow to a part of the battery, or it could be caused by a cell entering a state of self-heating that could lead to thermal runaway.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 1 Event Name: OVER_TEMP_ALARM
Fault: BMS Trip for: Sensor Temp [T] < Trip Min Temp [T], String [#], Sensor [#], Recorded at [timestamp]	FAULT: The BMS has detected that the TEMPERATURE measured by sensor # [#] in string # [#] has fallen below the Trip Min Temperature threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The temperature was measured to be [T] degrees C and the Trip Min Temperature threshold is currently set at [T] degrees C. This could be caused by insufficient heating of the battery's environment or by an obstruction of airflow to a part of the battery.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 3 Event Name: UNDER_TEMP_ALARM
Fault: BMS Trip for: SOC [%] > Trip Max SOC [%], String [#], Recorded at [timestamp]	FAULT: The BMS has detected that the STATE OF CHARGE estimated in string # [#] has exceeded the Trip Max SOC threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The SOC was measured to be [%]% and the Trip Max SOC threshold is currently set at [%]%. This could be caused the operational constraints on SOC being improperly configured in the charger or ESMS.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 15 Event Name: OVER_SOC_MAX_ALARM
Fault: BMS Trip for: SOC [%] < Trip Min SOC [%], String [#], Recorded at [timestamp]	FAULT: The BMS has detected that the STATE OF CHARGE estimated in string # [#] has fallen below the Trip Min SOC threshold. The BMS has actuated the circuit interrupt device in string # [#], removing it from service. The SOC was measured to be [%]% and the Trip Min SOC threshold is currently set at [%]%. In grid supporting applications, this could be caused the operational constraints on SOC being improperly configured in the energy storage management system. In non-grid supporting applications, this could be a normal fault that occurs when the battery has insufficient charge to support the load.	Model: 804 Address offset: 28 Register Name: Evt1 bitfield32: 13 Event Name: UNDER_SOC_MIN_ALARM

*These are the closest error codes in the SunSpec Energy Storage Model [B50], but they are missing identifiers for what string, module, and cell caused the error or warning event along with any timestamp information. Presumably these data would be available over a diagnostic communication connection.
**Timestamps are applied by the ESMS on receipt of the error code.

Annex E

(informative)

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