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Battery management controllers and associated methods

Abstract

A method for managing a plurality of batteries that are electrically coupled together includes (1) monitoring respective voltages of the plurality of batteries and (2) in response to a respective voltage of a first battery of the plurality of batteries reaching a first threshold value at a first time, reducing a charge or discharge rate of the first battery, relative to at least a second battery of the plurality of batteries. Charge and discharge rates may be adaptively managed such that each battery reaches the first threshold value at substantially the same time.

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References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
5341503	12/1993	Gladstein et al.	N/A	N/A
6160441	12/1999	Stratakos et al.	N/A	N/A
6262558	12/2000	Weinberg	N/A	N/A
6445244	12/2001	Stratakos et al.	N/A	N/A
6835491	12/2003	Gartstein	N/A	N/A
6984970	12/2005	Capel	N/A	N/A
7068017	12/2005	Willner et al.	N/A	N/A
8158877	12/2011	Klein et al.	N/A	N/A
8395519	12/2012	Cassidy	N/A	N/A
8686693	12/2013	Bhowmik et al.	N/A	N/A
9172120	12/2014	Pariseau	N/A	N/A
9331497	12/2015	Beaston	N/A	N/A
9425631	12/2015	Furtner	N/A	N/A
9431837	12/2015	Brockman	N/A	H02J 7/00306
9705341	12/2016	Komatsu et al.	N/A	N/A
9806545	12/2016	Fink	N/A	N/A
9865901	12/2017	Hwang	N/A	N/A
9912017	12/2017	Kuo	N/A	H01M 10/425
10018682	12/2017	Kaupp et al.	N/A	N/A
10153651	12/2017	Taylor et al.	N/A	N/A
10270262	12/2018	Kim et al.	N/A	N/A
10553851	12/2019	Kim	N/A	N/A
10734828	12/2019	Fasching et al.	N/A	N/A
10804690	12/2019	Ronne et al.	N/A	N/A
10981557	12/2020	Ye	N/A	B60W 20/13
10992149	12/2020	Kahn et al.	N/A	N/A
11237216	12/2021	Chang	N/A	G01R 31/388

2005/0121067	12/2004	Toyomura et al.	N/A	N/A
2005/0139258	12/2004	Liu et al.	N/A	N/A
2008/0236648	12/2007	Klein et al.	N/A	N/A
2008/0303503	12/2007	Wolfs	N/A	N/A
2009/0284078	12/2008	Zhang et al.	N/A	N/A
2009/0284232	12/2008	Zhang et al.	N/A	N/A
2009/0284240	12/2008	Zhang et al.	N/A	N/A
2009/0284998	12/2008	Zhang et al.	N/A	N/A
2010/0207455	12/2009	Erickson, Jr. et al.	N/A	N/A
2010/0253150	12/2009	Porter et al.	N/A	N/A
2010/0288327	12/2009	Lisi et al.	N/A	N/A
2010/0327659	12/2009	Lisi et al.	N/A	N/A
2011/0062784	12/2010	Wolfs	N/A	N/A
2011/0090607	12/2010	Luebke et al.	N/A	N/A
2011/0141644	12/2010	Hastings et al.	N/A	N/A
2011/0301772	12/2010	Zuercher et al.	N/A	N/A
2012/0013201	12/2011	Pariseau	N/A	N/A
2012/0043818	12/2011	Stratakos et al.	N/A	N/A
2012/0043823	12/2011	Stratakos et al.	N/A	N/A
2012/0043923	12/2011	Ikriannikov et al.	N/A	N/A
2012/0044014	12/2011	Stratakos et al.	N/A	N/A
2012/0112760	12/2011	Yoscovich et al.	N/A	N/A
2012/0119746	12/2011	Macris	N/A	N/A
2012/0133521	12/2011	Rothkopf et al.	N/A	N/A
2013/0092208	12/2012	Robbins	N/A	N/A
2013/0106194	12/2012	Jergovic et al.	N/A	N/A
2013/0170084	12/2012	Strobl et al.	N/A	N/A
2013/0176401	12/2012	Monari et al.	N/A	N/A
2014/0253045	12/2013	Poznar	N/A	N/A
2014/0368205	12/2013	Svensson et al.	N/A	N/A
2014/0373894	12/2013	Stratakos et al.	N/A	N/A
2016/0372940	12/2015	Canadi	N/A	N/A
2017/0123008	12/2016	Frias et al.	N/A	N/A
2018/0147947	12/2017	Gebhart	N/A	N/A
2019/0051892	12/2018	Yushin	N/A	H01G 11/32
2019/0198938	12/2018	Fujita et al.	N/A	N/A
2019/0361075	12/2018	Lee et al.	N/A	N/A
2020/0067324	12/2019	Zou	N/A	H01M 10/0525
2020/0127489	12/2019	Chen et al.	N/A	N/A
2020/0207219	12/2019	Slepchenkov et al.	N/A	N/A
2020/0321787	12/2019	Miller	N/A	H01M 10/441
2020/0350779	12/2019	Tikhonski et al.	N/A	N/A
2023/0011716	12/2022	Kahn et al.	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	**Application Date**	**Country**	**CPC**
202182410	12/2011	CN	F21S 9/03
2015200366	12/2014	WO	N/A

OTHER PUBLICATIONS

Walker, Geoffrey R., et al., “Cascaded DC-DC Converter Connection of Photovoltaic Modules”, IEEE Transactions on Power Electronics, vol. 19, No. 4, (Jul. 2004), 1130-1139. cited by applicant
Wolfs, Peter, et al., “Distributed Maximum Power Tracking for High Performance Vehicle Solar Arrays”, Australian Universities Power Engineering Conference (AUPEC 2004), (Sep. 2004), 6 pgs. cited by applicant
Anderson, R. Dyche et al., “Life-Balancing—A Better Way to Balance Large Batteries,” SAE World Congress Experience, Apr. 4-6, 2017, Detroit, Michigan, 6 pgs. cited by applicant
Rehman M. Muneeb UR et al., “Advanced Cell-level Control for Extending Electric Vehicle Battery Pack Lifetime”, IEEE, 2016, 8 pgs. cited by applicant
Abstract Only, Altaf, Faisal et al., “Simultaneous Thermal and State-of-Charge Balancing of Batteries: A Review”, 2014 lEEE Vehicle Power and Propulsion Conference (VPCC), 4 pgs. cited by applicant
Abstract Only, Barreras, Jorge V., “Multi-Objective Control of Balancing Systems for Li-Ion Battery Packs: A Paradigm Shift?”, 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), 4 pages. cited by applicant

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Background/Summary

RELATED APPLICATIONS (1) This application is a continuation of U.S. patent application Ser. No. 17/369,523, filed on Jul. 7, 2021, which is incorporated herein by reference.

BACKGROUND
(1) A battery is a device including one or more electrochemical cells that may be discharged to convert chemical energy into electrical energy. Batteries may be grouped into primary batteries and secondary batteries. A primary battery is single-use device which undergoes an irreversible change during its discharge. A secondary battery, in contrast, can be recharged by applying an electric current to the battery, and a secondary battery can therefore be discharged and recharged multiple times.
(2) Batteries are widely used as electrical power sources in applications where a continuous connection to a fixed electric power source, such as an electric utility grid, is undesirable or infeasible. For example, batteries are widely used to power mobile information technology devices, such as mobile telephones and tablet computers. Additionally, batteries are increasingly being used as a power source in vehicles, either as a vehicle's sole power source or to supplement a vehicle's internal combustion engine. It is anticipated that batteries will largely supplant internal combustion engines in future new vehicles.
(3) Furthermore, there is great interest in using batteries in electric infrastructure to store energy. For example, an electric utility may charge a battery to store energy when there is a surplus of electrical power, and the electric utility may subsequently discharge the battery to withdraw the stored energy when additional electrical power is needed. Accordingly, batteries are anticipated to be a key component in the ongoing transition from fossil fuel electrical power sources to renewable electric power sources, as batteries can compensate for the intermittent nature of renewable electric power sources.
(4) One popular battery is the Lithium-ion (Li-ion) battery. Examples of Li-ion batteries include

Lithium Cobalt Oxide (LCO) batteries, Lithium Manganese Oxide (LMO) batteries, Lithium Nickel Manganese Cobalt Oxide (NMC) batteries, Lithium Iron Phosphate (LFP) batteries, Lithium Nickel Cobalt Aluminum Oxide (NCA) batteries, and Lithium Titanate (LTO) batteries. Li-ion batteries advantageously have a high energy density relative to most other secondary batteries. However, Li-ion batteries can easily be damaged by operation outside of their intended operating range, such as by overcharging the battery or by excessively discharging the battery. Additionally, the high energy density of Li-ion batteries makes them susceptible to catching fire or exploding in case of battery damage or battery failure. Battery management systems, which control battery operation, such as battery charging and discharging, are therefore used with Li-ion batteries (and other batteries) to help achieve long battery life and safe battery operation.

SUMMARY

(5) In a first aspect, a method for managing a plurality of batteries that are electrically coupled together includes (a) monitoring respective voltages of the plurality of batteries and (b) in response to a respective voltage of a first battery of the plurality of batteries reaching a first threshold value at a first time, reducing a charge or discharge rate of the first battery, relative to at least a second battery of the plurality of batteries.

(6) In an embodiment of the first aspect, reducing the charge or discharge rate of the first battery relative to at least the second battery of the plurality of batteries includes changing operation of a first DC-to-DC converter electrically coupled to the first battery independently of operation of a second DC-to-DC converter electrically coupled to the second battery.

(7) In another embodiment of the first aspect, the first and second DC-to-DC converters are electrically coupled in series.

(8) In another embodiment of the first aspect, the method further includes increasing a charge or discharge rate of the second battery to compensate for reducing the charge or discharge rate of the first battery.

(9) In another embodiment of the first aspect, reducing the charge or discharge rate of the first battery includes changing operation of a first DC-to-DC converter electrically coupled to the first battery, and increasing the charge or discharge rate of the second battery comprises changing operation of a second DC-to-DC converter electrically coupled to the second battery.

(10) In another embodiment of the first aspect, the method further includes increasing the respective charge or discharge rate of the first battery in response to a respective voltage of the second battery reaching the first threshold value at a second time that is after the first time.

(11) In another embodiment of the first aspect, the method further includes, after step (b), adaptively managing charge or discharge rates of the plurality of batteries such that each battery reaches the first threshold value at substantially the same time.

(12) In another embodiment of the first aspect, adaptively managing charge or discharge rates of the plurality of batteries include changing a charge or discharge rate of the first battery relative to the second battery.

(13) In another embodiment of the first aspect, adaptively managing charge or discharge rates of the plurality of batteries includes changing a charge or discharge rate of the second battery relative to the first battery.

(14) In another embodiment of the first aspect, adaptively managing charge or discharge rates of the plurality of batteries includes using an iterative process to reduce a difference in time when the first and second batteries reach the first threshold value.

(15) In another embodiment of the first aspect, adaptively managing charge or discharge rates of the plurality of batteries includes using historical data from an energy storage system to determine how to adjust a charge or discharge rate of one or more of the plurality of batteries, such that each battery reaches the first threshold value at substantially the same time.

(16) In another embodiment of the first aspect, the respective voltages of the plurality of batteries include one of (a) actual battery voltages, (b) actual battery open circuit voltages, and (c) estimated

battery open circuit voltages.
(17) In another embodiment of the first aspect, the first threshold value corresponds to one of (a) a knee in a battery voltage versus state of charge curve and (b) a knee in a battery voltage versus time curve.
(18) In another embodiment of the first aspect, the first threshold value corresponds to one of (a) a predetermined change in the respective voltage of the first battery and (b) a predetermined rate of change in the respective voltage of the first battery.
(19) In another embodiment of the first aspect, each battery is a battery module including either (a) a plurality of electrochemical cells or (b) a single electrochemical cell.
(20) In a second aspect, a controller for managing a plurality of batteries that are electrically coupled together includes (1) one or more memories and (2) one or more processors communicatively coupled to the one or more memories. The one or more processors are configured to execute instructions stored in the one or memories to (1) monitor respective voltages of the plurality of batteries, and (2) in response to a respective voltage of a first battery of the plurality of batteries reaching a first threshold value at a first time, reduce a charge or discharge rate of the first battery, relative to at least a second battery of the plurality of batteries.
(21) In an embodiment of the second aspect, the one or more processors are further configured to execute instructions stored in the one or more memories to increase a charge or discharge rate of the second battery to compensate for reducing the charge or discharge rate of the first battery.
(22) In another embodiment of the second aspect, the one or more processors are further configured to execute instructions stored in the one or more memories to increase the respective charge or discharge rate of the first battery, in response to a respective voltage of the second battery reaching the first threshold value at a second time that is after the first time.
(23) In another embodiment of the second aspect, the one or more processors are further configured to execute instructions stored in the one or more memories to adaptively manage charge or discharge rates of the plurality of batteries such that each battery reaches the first threshold value at substantially the same time.
(24) In another embodiment of the second aspect, the one or more processors are further configured to execute instructions stored in the one or more memories to adaptively manage charge or discharge rates of the plurality of batteries using an iterative process.
(25) In another embodiment of the second aspect, the one or more processors are further configured to execute instructions stored in the one or more memories to adaptively manage charge or discharge rates of the plurality of batteries using historical data from an energy storage system.
(26) In another embodiment of the second aspect, the first threshold value corresponds to one of (a) a knee in a battery voltage versus state of charge curve and (b) a knee in a battery voltage versus time curve.
(27) In another embodiment of the second aspect, the first threshold value corresponds to one of (a) a predetermined change in the respective voltage of the first battery and (b) a predetermined rate of change in the respective voltage of the first battery.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a schematic diagram of an energy storage system including a stack of batteries and power converters, according to an embodiment.
(2) FIG. **2** is a schematic diagram of a battery that is a single electrochemical cell.
(3) FIG. **3** is a schematic diagram of a battery including a plurality of electrochemical cells electrically coupled in parallel.
(4) FIG. **4** is a schematic diagram of a battery including a plurality of electrochemical cells

electrically coupled in series.
(5) FIG. **5** is a schematic diagram of a battery including a plurality of electrochemical cells electrically coupled in a series/parallel combination.
(6) FIG. **6** is a schematic diagram of one embodiment of a battery management controller of the FIG. **1** energy storage system.
(7) FIG. **7** is a schematic diagram of another embodiment of a battery management controller of the FIG. **1** energy storage system.
(8) FIG. **8** is a schematic diagram of one embodiment of a power converter of the FIG. **1** energy storage system.
(9) FIG. **9** is a schematic diagram of one embodiment of a power stage of the FIG. **8** power converter.
(10) FIG. **10** is a schematic diagram of an alternate embodiment of the FIG. **1** electric energy storage system including two stacks.
(11) FIG. **11** is a schematic diagram of an alternate embodiment of the FIG. **1** energy storage system where batteries in a stack are indirectly electrically coupled in parallel via respective power converters.
(12) FIG. **12** is a graph of open circuit voltage versus state of charge for two different battery types.
(13) FIG. **13** is a graph of battery voltage versus time illustrating one example of operation of a battery management controller configured to mitigate effects of dead band operation on battery state of charge balance during charging, according to an embodiment.
(14) FIG. **14** is a schematic diagram of a stack illustrating an example of how a battery management controller may compensate for decreasing charge rate of a battery of the stack, according to an embodiment.
(15) FIG. **15** is a schematic diagram of a stack illustrating another example of how a battery management controller may compensate for decreasing charge rate of a battery of the stack, according to an embodiment
(16) FIG. **16** is a graph of battery voltage versus time illustrating one example of operation of a battery management controller configured to mitigate effects of the dead band operation on battery state of charge balance during discharging, according to an embodiment.
(17) FIG. **17** is a schematic diagram of a stack illustrating an example of how a battery management controller may compensate for decreasing discharge rate of a battery of the stack, according to an embodiment.
(18) FIG. **18** is a schematic diagram of a stack illustrating an example of how a battery management controller may compensate for decreasing discharge rate of a battery of the stack, according to an embodiment.
(19) FIG. **19** is a flow chart of a method for managing a plurality of batteries that are electrically coupled together, to mitigate effects of dead band operation on battery state of charge balancing, according to an embodiment.

DETAILED DESCRIPTION OF THE EMBODIMENTS

(20) Disclosed herein are new battery management controllers and associated methods which significantly advance the state of the start. Certain embodiments of the new controllers and methods advantageously help achieve greater battery throughput, greater battery lifetime, and/or greater battery safety, than what is feasible when using conventional battery management controllers. For example, certain embodiments are configured to improve battery state of charge balancing in applications where batteries exhibit an extremely flat open circuit voltage (OCV) characteristic (dead band), such as in applications including LFP batteries. In this document, the term "substantially" means within ten percent. For example, X is considered substantially equal to Y if X is greater than or equal to 90 percent of Y and less than or equal to 110 percent of Y. Furthermore, in this document, equivalent series resistance (ESR) of a battery may include resistance of electrical interconnects to and within the battery as well as equivalent series resistance

of electrochemical cells within the battery.

(21) FIG. **1** is a schematic diagram of an energy storage system **100** including a battery management controller **102**, a stack **104**, a source/load **106**, and an electric power bus **108**, where battery management controller **102** is one embodiment of the new battery management controllers disclosed herein. Source/load **106** can operate as either an electric power source or as a load. Source/load **106** provides electric power to stack **104** when source/load **106** operates as an electric power source, and source/load **106** consumes electric power from stack **104** when source/load **106** operates as a load. In some embodiments, source/load **106** is an inverter which interfaces energy storage system **100** with an alternating current (AC) electric power system (not shown). In some other embodiments, source/load **106** is a direct current-to-direct current (DC-to-DC) converter which interfaces energy storage system **100** with a direct current (DC) electric power system (not shown). In certain additional embodiments, source/load **106** is an electromechanical device, e.g. a combination motor and generator, that can generate electric power as well as consume electric power. Additionally, source/load **106** may include a plurality of elements. For example, source/load **106** may include a photovoltaic array (not shown) as well as an inverter (not shown) electrically coupling energy storage system **100** with an AC electric power system (not shown). However, source/load **106** can take other forms without departing from the scope hereof.

(22) Stack **104** includes N batteries **110** and N power converters **112**, where N is an integer that is greater than or equal to one. In this document, specific instances of an item may be referred to by use of a numeral in parentheses (e.g. battery **110**(**1**)) while numerals without parentheses refer to any such item (e.g. batteries **110**). Each battery **110** is electrically coupled to input ports **114** and **116** of a respective power converter **112**. Each battery **110** and its respective power converter **112** are sometimes referred to as a battery management system (BMS) node. Output ports **118** and **120** of power converters **112** are electrically coupled in series between stack ports **122** and **124**. Specifically, output port **120**(**1**) of power converter **112**(**1**) is electrically coupled to output port **118**(**2**) of power converter **112**(**2**), output port **120**(**2**) of power converter **112**(**2**) is electrically coupled to output port **118**(**3**) of power converter **112**(**3**) (not explicitly shown in FIG. **1**), and so on. Output port **118**(**1**) of power converter **112**(**1**) is electrically coupled to stack port **122**, and output port **120**(N) of power converter **112**(N) is electrically coupled to stack port **124**. Electric power bus **108** electrically couples stack ports **122** and **124** to source/load **106**.

(23) Each battery **110** includes one or more electrochemical cells. For example, FIGS. **2-5** are schematic diagrams of possible embodiments of a battery **110**, although batteries **110** are not limited to these embodiments. FIG. **2** is a schematic diagram of an electrochemical cell **202**, which is an embodiment of a battery **110** where the battery **110** is a single electrochemical cell. FIGS. **3-5**, in contrast, are schematic diagrams of embodiments of a battery **110** where the battery is an assembly, e.g. a module, of a plurality of electrochemical cells that are electrically coupled together. Specifically, FIG. **3** is a schematic diagram of a battery **300** including M electrochemical cells **302** electrically coupled in parallel, and FIG. **4** is a schematic diagram of a battery **400** including M electrochemical cells **402** electrically coupled in series, where M is an integer greater than one. FIG. **5** is a schematic diagram of a battery **500** including a plurality of electrochemical cells **502** electrically coupled in a series/parallel combination. In some embodiments, electrochemical cells **202**, **302**, **402**, and **502** are Li-ion chemical cells, e.g., LCO chemical cells, LMO chemical cells, NMC chemical cells, LFP chemical cells, NCA chemical cells, or LTO chemical cells. However, electrochemical cells **202**, **302**, **402**, and **502** can be other types of electrochemical cells, including future-developed electrochemical cells, without departing from the scope hereof.

(24) Referring again to FIG. **1**, battery management controller **102** is configured to generate a respective control signal C for each power converter **112**, to enable battery management controller **102** to control operation of power converters **112**. Additionally, battery management controller **102** is configured to receive a respective feedback signal F from each power converter **112.** In some

embodiments, each feedback signal F specifies, for its respective power converter **112** and associated battery **110**, one or more of (a) voltage V.sub.bat across battery **110** (e.g., voltage across terminals of the battery), (b) current I.sub.bat flowing through battery **110**, (c) voltage V.sub.con across the power converter **112**'s output ports **118** and **120**, (d) current I.sub.bus flowing through the power converter **112**'s output ports **118** and **120**, and (e) temperature of battery **110**.

(25) Signals C and F are communicated between controller **102** and power converters **112**, for example, via one or more electrical conductors (not shown), one or more optical conductors (not shown), and/or one or more wireless transceivers (not shown). Although battery management controller **102** is illustrated as being a discrete element, battery management controller **102** could be at least partially incorporated in one or more batteries **110** and/or one or more power converters **112**. Additionally, battery management controller **102** could be formed of multiple constituent elements which need not be co-packaged or even disposed at a common location. For example, in certain embodiments, at least some elements of battery management controller **102** are embodied by a distributed computing system, e.g. a “cloud” computing system, such as discussed below with respect to FIG. **7**. As another example, in some embodiments, elements of battery management controller **102** are distributed among one or more stack controllers (not shown) and a central host controller (not shown), of energy storage system **100**.

(26) FIG. **6** is a schematic diagram of a battery management controller **600**, which is one possible embodiment of battery management controller **102**. Battery management controller **600** includes a processor **602**, a memory **604**, and interface circuitry **606**. Processor **602** is communicatively coupled to each of memory **604** and interface circuitry **606**, and processor **602** is configured to execute instructions **608**, e.g., in the form of software and/or firmware, stored in memory **604**, to generate control signals C at least partially in response to feedback signals F received from power converters **112**. In some embodiments, battery management controller **600** is further configured to receive instructions and/or data from an external source, such as a battery data processing engine (not shown) remote from energy storage system **100**. The battery data processing engine, for example, provides instructions to processor **602** to control at least some aspects of energy storage system **100** based on prior experience with other energy storage systems having on or more common traits with energy storage system **100**.

(27) Interface circuitry **606** interfaces processor **602** with one or more communication mediums (not shown) for transmitting signals C and F between battery management controller **600** and power converters **112**. In some embodiments, interface circuitry **606** includes one or more electrical transceivers, optical transceivers, and/or wireless transceivers. Battery management controller **600** could include one or more additional processors and/or memories, and the elements of battery management controller **600** need not be co-packaged or even disposed at a common location. Additionally, battery management controller **600** could be modified to replace processor **602** and memory **604** with analog and/or digital circuitry which performs the same functions as processor **602** and memory **604**.

(28) FIG. **7** is a schematic diagram of a battery management controller **700**, which is another possible embodiment of battery management controller **102**. Battery management controller **700** includes a system processor **702**, a system memory **704**, and interface circuitry **706** disposed at or near stack **104**. Battery management controller **700** further includes a global processor **710** and a global memory **712** remote from stack **104**. Although each of global processor **710** and global memory **712** are depicted as a single element, one or more of global processor **710** and global memory **712** may include multiple sub-elements which need not be disposed at a common location. For example, in some embodiments, global processor **710** and global memory **712** are implemented in a distributed computing environment. Networks/Internet **714** communicatively couple system processor **702** and global processor **710**, and networks/Internet **714** need not be part of battery management controller **700**. Additionally, global processor **710** and global memory **712** may be shared by one or more energy storage systems in addition to energy storage system **100**, such that

global processor **710** and global memory **712** are effectively part of a battery management controller of one or more additional energy storage systems.
(29) System processor **702** is communicatively coupled to each of system memory **704** and interface circuitry **706**, and system processor **702** is configured to execute instructions **708**, e.g. in the form of software and/or firmware, stored in system memory **704**, to generate control signals C at least partially in response to feedback signals F received from power converters **112** and instructions/data **716** received from global processor **710**. Interface circuitry **706** is analogous to interface circuitry **606** of FIG. **6**.
(30) Global processor **710** is configured to execute instructions **718**, in the form of software and/or firmware, stored in global memory **712** to perform one or more of the following functions. In some embodiments, global processor **710** is configured to receive system data **720** from system processor **702**, where system data **720** represents one or more aspects of energy storage system **100**. System processor **702** is configured to determine system data **720**, for example, at least partially based on feedback signals F from power converters **112**. By way of example and not limitation, system data **720** may include battery **110** temperature, battery voltage V.sub.bat, battery current I.sub.bat, the type of batteries **110** in energy storage system **100**, the configuration of batteries **110** in energy storage system **100**, manufacturing information for batteries **110** in energy storage system **100**, operating history of batteries **110** in energy storage system **100**, maintenance history of batteries **110** in energy storage system **100**, etc. System data **720** is optionally encrypted, compressed, and/or preprocessed (e.g., identifying various degradation mechanisms and/or hazardous operating conditions) before being sent from system processor **702** to global processor **710**.
(31) Global processor **710** compares system data **720** to aggregate data **722** to find common traits between the two data sets. Aggregate data **722** includes data from multiple energy storage systems, e.g. from tens, hundreds, or even thousands of energy storage systems. Global processor **710** optionally adds information it receives from energy storage systems to aggregate data **722**, such that aggregate data **722** grows over time. Examples of common traits between system data **720** and aggregate data **722** include, but are not limited to, batteries operating under the same or similar conditions, batteries with the same or similar operation duration, batteries with the same or similar energy throughput, batteries from a common manufacturing lot, batteries with the same or similar installation, batteries stored under the same or similar conditions, batteries with the same or similar maintenance history, and batteries with similar arc fault signatures. In some embodiments, global processor **710** uses self-learning methodologies (e.g., machine-learning, deep-learning, or even multi-modal machine learning) to identify common traits between system data **720** and aggregate data **722**.
(32) Global processor **710** subsequently identifies data that is applicable to energy storage system **100** from the common traits between system data **720** and aggregate data **722**. More specifically, global processor **710** identifies data in aggregate data **722** that is associated with energy storage systems having common traits with energy storage system **100**, as being applicable data. For example, global processor **710** may identify data from an energy storage system having the same type of batteries as energy storage system **100** as being applicable data. As another example, global processor **710** may identify data from an energy storage system operating under similar conditions to energy storage system **100** as being applicable data. The applicable data may be either indirectly related or directly related to data associated with energy storage systems having common traits with energy storage system **100**. In some embodiments, global processor **710** uses self-learning methodologies (e.g., machine-learning, deep-learning, or even multi-modal machine learning) to identify the applicable data from aggregate data **722**.
(33) Global processor **710** determines instructions/data **716** from the applicable data. Instructions/data **716** may include instructions for energy storage system **100** based on the applicable data, and/or instructions/data **716** may include the applicable data itself. Global processor **710** sends instructions/data **716** to system processor **702**. Energy storage system **100**

optionally uses instructions/data **716** to manage one or more aspects of energy storage system **100**. For example, in particular embodiments, battery management controller **700** uses instructions/data **716** to build or refine models of batteries **110**, such as for controlling battery **110** charging/discharging or for identifying and/or mitigating degradation or failure mechanisms of batteries **110**.

(34) Referring again to FIG. **1**, each power converter **112** buffers its respective battery **110** from electric power bus **108**, and as discussed above, each power converter **112** generates a respective feedback signal F for controller **102**. FIG. **8** is a schematic diagram of a power converter **800**, which is one possible embodiment of a power converter **112**. Power converter **800** includes a power stage **802**, a local control module **804**, a temperature sensor **806**, a first switching device **808**, a second switching device **810**, a third switching device **812**, and a fourth switching device **814**. In some alternate embodiments, temperature sensor **806** is separate from power converter **800**, e.g., temperature sensor **806** could be part of a battery **110**, instead of part of power converter **800**. Additionally, one or more of first switching device **808**, second switching device **810**, third switching device **812**, and fourth switching device **814** may be omitted, such as in embodiments where the functionality realized by the switching devices is not required, or in embodiments where the functionality realized by the switching devices can be achieved by switching devices (not shown) within power stage **802**. In this document, the term “switching device” includes, but is not limited to, one or more transistors, e.g., field effect transistors (FETs), bipolar junction transistors (BJTs), and/or insulated gate bipolar junction transistors (IGBTs), as well as one or more relays, contactors, or similar devices that are capable of opening and closing a circuit in response to a signal. Additionally, one or more of switching devices **808**, **810**, **812**, and **814** can be replaced with, or supplemented by, one or more diodes, without departing from the scope hereof.

(35) Power stage **802** is electrically coupled between (a) input ports **114** and **116** and (b) output ports **118** and **120**. Power stage **802** is configured to perform one or more of the following power conversion functions, in response to switching signals ϕ generated by local control module **804**: (a) transform voltage V.sub.bat across input ports **114** and **116** to voltage V.sub.con across output ports **118** and **120**, (b) transform voltage V.sub.con across output ports **118** and **120** to voltage V.sub.bat across input ports **114** and **116**, (c) transform current I.sub.bat flowing through battery **110** and input ports **114** and **116** to current I.sub.bus flowing through output ports **118** and **120** and electric power bus **108**, and (d) transform current I.sub.bus flowing through output ports **118** and **120** and electric power bus **108** to current I.sub.bat flowing through battery **110** and input ports **114** and **116**. In some embodiments, power stage **802** includes one or more of a non-isolated DC-to-DC switching converter, an isolated DC-to-DC switching converter, and a linear regulator.

(36) For example, FIG. **9** is a schematic diagram of a power stage **900**, which is one possible embodiment of power stage **802** of FIG. **8**. Power stage **900** includes an inductor **902**, a first switching device **904**, a second switching device **906**, a first capacitor **908**, and a second capacitor **910**. Although inductor **902** is depicted as being a discrete element, inductor **902** could be distributed inductance of a circuit including power stage **900**. First switching device **904** and second switching device **906** are respectively controlled by switching signals ϕ(**1**) and ϕ(**2**) generated by local control module **804** of FIG. **8**. Magnitude of voltage V.sub.con is greater than or equal to magnitude of voltage V.sub.bat in power stage **900**. Power stage **900** increases voltage magnitude from V.sub.bat to V.sub.con and supports bidirectional current flow. Electric power can flow in a direction **912**, e.g., when a battery **110** electrically coupled to power stage **900** is discharging into source/load **106**. Electric power can also flow in direction **914**, e.g., when source/load **106** is charging a battery **110** electrically coupled to power stage **900**.

(37) Referring again to FIG. **8**, local control module **804** is configured to generate switching signals ϕ in response to control signals C received from battery management controller **102**. Additionally, local control module **804** is configured to monitor one or more of the following parameters and generate feedback signals F to convey these monitored parameters to battery management

controller **102**: (a) temperature (**7**) of a battery **110** electrically coupled to power converter **800**, (b) voltage V.sub.bat, (c) current I.sub.bat, (d) voltage V.sub.con, and (e) current I.sub.bus. Local control module **804** is optionally further configured to include additional information in feedback signals F, such as information on a respective battery **110** (e.g., battery **110** type, manufacturing information for battery **110**, operating history for battery **110**, and/or maintenance history for battery **110**). Furthermore, local control module **804** is configured to generate signals S.sub.1, S.sub.2, S.sub.3, and S.sub.4, for respectively controlling switching devices **808**, **810**, **812**, and **814**, in response to control signals C from battery management controller **102**. Local control module **804** causes switching device **808** to open, for example, to isolate power stage **802** from its respective battery **110**. Local control module **804** may cause switching device **810** to close to discharge a battery **110** electrically coupled to power stage **802**, such as in an emergency, in response to determining that battery **110** is unsafe, or in preparation for electric power system **100** maintenance. In some embodiments, a resistor (not shown) is electrically coupled in series with switching device **810** to facilitate controlled discharge of the battery, or switching device **810** is replaced with a current source configured to perform a controlled discharge of the battery. Local control module **804** causes switching device **812** to open, for example, to isolate power stage **802** from electric power bus **108**. Additionally, local control module **804** may cause switching device **814** to close to enable current I.sub.bus to bypass power stage **802**.

(38) Referring again to FIG. **1**, inclusion of a respective power converter **112** between each battery **110** and electric power bus **108** buffers batteries **110** from electric power bus **108**, as discussed above. Consequently, battery management controller **102** can individually control charging and discharging of each battery **110**, thereby enabling battery management controller **102** to help maximize battery **110** throughput, battery **110** lifetime, and battery **110** safety. Additionally, certain embodiments of battery management controller **102** are configured to control operation of power converters **112** via control signals C in a matter which controls a respective bus contribution voltage of each battery **110**, i.e. V.sub.con of each power converter **112**, where bus contribution voltages V.sub.con sum to bus voltage V.sub.bus across source/load **106**. As a result, a weaker battery **110** will not limit performance of a stronger battery **110** in stack **104**. In a conventional stack where batteries are directly connected in series, in contrast, stack performance will be limited by a weakest battery in the stack. Furthermore, some embodiments of battery management controller **102** are configured to control operation of power converters **112** via control signals C to control current I.sub.bus flowing through power converter output ports **118** and **120**.

(39) Energy storage system **100** can be modified to include additional stacks **104** and/or have a different configuration of stacks **104**. For example, FIG. **10** is a schematic diagram of an energy storage system **1000**, which is an alternate embodiment of energy storage system **100** which includes two instances of stack **104**, i.e. stacks **104**(**1**) and **104**(**2**). Battery management controller **102**, as well as details of stacks **104**(**1**) and **104**(**2**), are not shown in FIG. **10** for illustrative clarity. Stacks **104**(**1**) and **104**(**2**) need not have the same configuration. For example, stacks **104**(**1**) and **104**(**2**) could have different numbers of batteries **110** and respective power converters **112**, because battery management controller **102** can control the power converters **112** of each stack **104** to compensate for differing number of batteries **110** among stacks **104**. Battery management controller **102** is also configured to control partitioning of current I.sub.bus, and/or electrical power flow between stacks **104** and source/load **106**, as well as among stacks **104**(**1**) and **104**(**2**).

(40) FIG. **11** is a schematic diagram of an energy storage system **1100**, which is an alternate embodiment of energy storage system **100** where stack **104** is replaced with a stack **1104**. Batteries **110** are indirectly electrically coupled in parallel via their respective power converters **112** in stack **1104**. Source/load **106** and electric power bus **108** are not shown in FIG. **11** for illustrative clarity. Voltage V.sub.con across each power converter **112**'s output ports **118** and **120** is equal to voltage V.sub.bus in electric power system **1100**, due to the parallel connection of power converters **112** in stack **1104**. However, each power converter **112** has a respective current I.sub.con flowing through

its output ports **118** and **120** to electric power bus **108**.

(41) Referring again to FIG. **1**, it is desirable to balance state of charge (SOC) of batteries **110**, to promote battery throughput, battery lifetime, and battery safety. Balanced SOC may be substantially achieved, for example, by balancing voltages V.sub.bat of batteries **110** via appropriate control of power converters **112** by battery management controller **102**. For example, certain embodiments of battery management controller **102** are configured to balance voltages V.sub.bat at least partially by (1) determining each voltage V.sub.bat, e.g. from feedback signals F, and (2) controlling power converters **112** via control signals C to distribute power among batteries **110** based at least partially based on a difference between each voltage V.sub.bat and an average voltage V.sub.bat,avg of all batteries **110**. For example, in certain embodiments, battery management controller **102** assigns a battery **110** with a smallest value of V.sub.bat the most power during charging, and battery management controller **102** assigns a battery **110** with a largest value of V.sub.bat the most power during discharging, to cause battery voltages V.sub.bat to at least substantially converge during a charge or discharge cycle or over multiple charge or discharge cycles.

(42) Some batteries have a relatively flat voltage versus SOC curve during certain operating regions. For example, FIG. **12** is a graph of OCV versus SOC for a NMC battery consisting of a single NMC electrochemical cell and a LFP battery consisting of a single LFP electrochemical cell. Curve **1202** corresponds to the NMC battery, and curve **1204** corresponds to the LFP battery. Battery operation may be divided into three ranges in this example—operating region 1 (OR1), operating region 2 (OR2), and operating region 3 (OR3). Operating region 1 corresponds to small SOC, operating region 2 corresponds to moderate SOC, and operating region 3 corresponds to large SOC. As evident from FIG. **12**, while the NMC battery has a significant slope in operating region 2, the LFP battery has minimal slope in operating region 2, where slope is equal to change in OCV over change in SOC (ΔOCV/ΔSOC). Operating region 2 for the LFP battery may be referred to as a “dead band” region for the LFP battery, due to the essentially flat OCV versus SOC curve during this region. It may be difficult to balance SOC among batteries **110** operating in their dead bands because battery voltage V.sub.bat does not appreciably change as the batteries are charged or discharged, and battery management controller **102** therefore receives minimal feedback during operation in the dead band region. For example, batteries may become unbalanced during dead band operation because there is little change in battery voltage as battery SOC varies. Consequently, batteries of a stack may exit the dead band at different times, causing pack charging or discharging to terminate early due to one or more out-of-balance batteries hitting a maximum or minimum threshold value, such as a voltage threshold value or a SOC threshold value, before other batteries of the stack. Furthermore, battery cells that are repeatedly cycled over a wider SOC range than other battery cells will degrade more rapidly than the other battery cells, shortening their life, and therefore, the life and lifetime energy throughput of a stack containing the battery cells.

(43) Certain embodiments of battery management controller **102**, however, are configured to mitigate effects of dead band operation on battery SOC balancing, which advantageously helps achieve maximum battery **110** energy throughput and maximum battery **110** life. For example, in some embodiments, when change in voltage of a first battery **110** of stack **104** reaches a threshold value, battery management controller **102** controls a respective power converter **112** of the first battery **110** to decrease charge or discharge rate of the first battery. The threshold value corresponds to, for example, either (1) a predetermined change in battery voltage or (2) a predetermined rate of change in battery voltage, such change in battery voltage over SOC or over time. Accordingly, the threshold value may correspond to a “knee” in a battery voltage versus SOC curve or a battery voltage versus time curve. For example, knees occur in the FIG. **12** LFP battery voltage curve at times t.sub.1 and t.sub.2. Decreasing charge or discharge rate of the first battery **110** when it reaches the threshold value or knee allows the remaining batteries in stack **104** to catch up with the first battery, i.e., for the remaining batteries **110** to approximately reach the same battery voltage as

the first battery **110**, thereby improving SOC balance among batteries **110** in stack **104**. Battery management controller **102** returns the first battery **110** to normal operation, i.e., it increases charge/discharge rate of the first battery **110** to a normal value, in response to the remaining batteries **110** in stack **104** catching up with the first battery **110**. Battery **110** voltage that is monitored during this operation is, for example, actual battery voltage V.sub.bat, estimated open circuit voltage V.sub.oc, or actual open circuit voltage V.sub.oc.

(44) The fact that each battery **110** is buffered from electric power bus **108** by a respective power converter **112** enables battery management controller **102** to decrease charge or discharge rate of the first battery **110** independent of other batteries **110** of stack **104**. Additionally, in certain embodiments, battery management controller **102** is configured to change charge or discharge rate of one or more other batteries **110** in stack **104** to compensate for decreasing charge or discharge rate of the first battery **110** while mitigating effects of battery **110** dead band operation, such as to maintain constant magnitude of voltage V.sub.bus and/or power into or out of stack **104**.

(45) FIG. **13** is a graph of battery voltage versus time illustrating one example of operation of an embodiment of battery management controller **102** configured to mitigate effects of dead band operation on SOC balancing during charging. The FIG. **13** example assumes that N is equal to three, i.e., there are three batteries **110** in stack **104**. Curve **1302** corresponds to a voltage V.sub.bat(**1**) of a first battery **110**(**1**) in stack **104**, curve **1304** corresponds to a voltage V.sub.bat(**2**) of a second battery **110**(**2**) in stack **104**, and curve **1306** corresponds to a voltage V.sub.bat(**3**) of a third battery **110**(**3**) in stack **104**. Voltages of the batteries **110** are, for example, either actual battery voltage V.sub.bat, estimated open circuit voltage V.sub.oc, or actual open circuit voltage V.sub.oc. Voltage V.sub.bat(**1**) of first battery **110**(**1**) reaches a threshold value, corresponding to a predetermined change in battery voltage, at time t.sub.1. In response, battery management controller **102** reduces a charge rate of the first battery **110**(**1**), to allow second and third batteries **110**(**2**) and **110**(**3**) to catch up with the first battery **100**(**1**). Voltage V.sub.bat(**2**) of second battery **110**(**2**) reaches the threshold value at time t.sub.2, and in response, battery management controller **102** reduces a charge rate of second battery **110**(**2**), to allow third battery **110**(**3**) to catch up with the first and second batteries. Voltage V.sub.bat(**3**) of third battery **110**(**3**) reaches the threshold value at time t.sub.3, and in response, battery management controller **102** increases respective charge rates of first and second batteries **110**(**1**) and **110**(**2**) and thereby returns the first and second batteries to normal operation. Third battery **110**(**3**) continues normal operation after time t.sub.3. Thus, battery management controller **102** approximately equalizes SOC of the three batteries **110** by time t.sub.3.

(46) Reducing charge rate of first battery **110**(**1**) at time t.sub.1 will change voltage V.sub.bus and power being absorbed by stack **104**. Accordingly, some embodiments of battery management controller **102** are further configured to increase charge rate of one or more other batteries **110** at time t.sub.1, to compensate for the decrease in charge rate of battery **110**(**1**) at time t.sub.1, and thereby maintain constant voltage V.sub.bus and/or power absorption of stack **104**. Similarly, some embodiments of battery management controller **102** are further configured to increase charge rate of one or more other batteries **110** at time t.sub.2, to compensate for the decrease in charge rate of battery **110**(**2**) at time t.sub.2, and thereby maintain constant voltage V.sub.bus and/or power absorption of stack **104**. Increasing charge rate of one or more batteries to compensate for decrease in charge rate of other batteries may also advantageously reduce time required for batteries at lower SOC to catch up with batteries at higher SOC.

(47) For example, FIG. **14** is a schematic diagram of a stack **1404**, which is an embodiment of stack **104** including the three instances of battery **110**, i.e., batteries **110**(**1**)-**110**(**3**) discussed above in the example of FIG. **13**. FIG. **14** includes notation to the left of each battery **110** indicating an example change in charge rate at time t.sub.1. In the FIG. **14** example, battery management controller **102** controls power converter **112**(**1**) to reduce charge rate of battery **110**(**1**) by ΔCR.sub.a, at time t.sub.1 to allow SOC of batteries **110**(**2**) and **110**(**3**) to catch up with SOC of

battery **110**(**1**). Battery management controller **102** also controls power converters **112**(**2**) and **112**(**3**) to increase respective charge rates of batteries **110**(**2**) and **110**(**3**) at time t.sub.1 by ΔCR.sub.a/2 to compensate for the decrease in charge rate of battery **110**(**1**), thereby maintaining constant V.sub.bus and power absorbed by stack **1404**.

(48) Additionally, FIG. **15** is a schematic diagram of stack **1404** illustrating an example of how battery management controller **102** might adjust battery charge rate to compensate for decrease in charge rate of battery **110**(**2**) at time t.sub.2. In this example, battery management controller **102** controls power converter **112**(**2**) to decrease charge rate of battery **110**(**2**) by ΔCR.sub.b at time t.sub.2 to allow SOC of battery **110**(**3**) to catch up to SOC of batteries **110**(**1**) and **110**(**2**). Battery management controller **102** also controls power converter **112**(**3**) to increase rate of charge of battery **110**(**3**) by ΔCR.sub.b to compensate for the decrease in charge rate of battery **110**(**2**), thereby maintaining constant V.sub.bus and power absorbed by stack **1404**.

(49) It is appreciated that battery management controller **102** could compensate for change of battery charge rates in manners other than those illustrated in the examples of FIGS. **14** and **15**. For example, battery management controller **102** could (a) control power converter **112**(**2**) to increase charge rate of battery **110**(**2**) by Δ3CR.sub.a/4 at time t.sub.1 and (b) control power converter **112**(**3**) to increase charge rate of battery **110**(**3**) by ΔCR.sub.a/4 at time t.sub.1, to compensate for decrease in charge rate of battery **110**(**1**) ΔCR.sub.a at time t.sub.1, instead of implementing the method illustrated in FIG. **14**.

(50) FIG. **16** is a graph of battery voltage versus time illustrating one example of operation of an embodiment of battery management controller **102** configured to mitigate effects of dead band operation on SOC balancing during discharging. Like the FIG. **13** example, the FIG. **16** example assumes that N is equal to three, i.e., there are three batteries in stack **104**. Curve **1602** corresponds to a voltage V.sub.bat(**1**) of a first battery **110**(**1**) in stack **104**, curve **1604** corresponds to a voltage V.sub.bat(**2**) of a second battery **110**(**2**) in stack **104**, and curve **1606** corresponds to a voltage V.sub.bat(**3**) of a third battery **110**(**3**) in stack **104**. Voltages of the batteries **110** are, for example, either actual battery voltage V.sub.bat, estimated open circuit voltage V.sub.oc, or actual open circuit voltage V.sub.oc. Voltage V.sub.bat(**1**) of first battery **110**(**1**) reaches a threshold value, corresponding to a predetermined change in battery voltage, at time t.sub.1. In response, battery management controller **102** reduces a discharge rate of first battery **110**(**1**), to allow the second and third batteries **110** to catch up with first battery **100**(**1**). Voltage V.sub.bat(**3**) of third battery **110**(**3**) reaches the threshold value at time t.sub.2, and in response, battery management controller **102** reduces a discharge rate of the third battery **110**(**3**), to allow second battery **110**(**2**) to catch up with the first and third batteries. Voltage V.sub.bat(**2**) of second battery **110**(**2**) reaches the threshold value at time t.sub.3, and in response, battery management controller **102** increases discharge rate of first and third batteries **110**(**1**) and **110**(**3**) and thereby returns the first and third batteries to normal operation. Second battery **110**(**2**) continues normal operation after time t.sub.3. Thus, battery management controller **102** approximately equalizes SOC of the three batteries **110** by time t.sub.3.

(51) Reducing discharge rate of first battery **110**(**1**) at time t.sub.1 will change voltage V.sub.bus and power being provided by stack **104**. Accordingly, some embodiments of battery management controller **102** are further configured to increase discharge rate of one or more other batteries **110** at time t.sub.1, to compensate for the decrease in discharge rate of battery **110**(**1**) at time t.sub.1, and thereby maintain constant voltage V.sub.bus and/or power provided by stack **104** while compensating for battery **110**(**1**) entering a dead band operating region. Similarly, some embodiments of battery management controller **102** are further configured to increase discharge rate of one or more other batteries **110** at time t.sub.2, to compensate for the decrease in charge rate of battery **110**(**3**) at time t.sub.2, and thereby maintain constant voltage V.sub.bus and/or power provided by stack **104** while compensating for battery **110**(**3**) entering a dead band operating region. Increasing discharge rate of one or more batteries to compensate for decrease in discharge

rate of other batteries may also advantageously reduce time required for batteries at higher SOC to catch up with batteries at low SOC.
(52) For example, FIG. **17** is a schematic diagram of a stack **1704**, which is an embodiment of stack **104** including the three instances of battery **110**, i.e., batteries **110**(**1**)-**110**(**3**) discussed above in the example of FIG. **16**. FIG. **17** includes notation to the left of each battery **110** indicating an example change in discharge rate at time t.sub.1. In the FIG. **17** example, battery management controller **102** controls power converter **112**(**1**) to reduce discharge rate of battery **110**(**1**) by ΔDR.sub.a, at time t.sub.1 to allow SOC of batteries **110**(**2**) and **110**(**3**) to catch up with SOC of battery **110**(**1**). Battery management controller **102** also controls power converters **112**(**2**) and **112**(**3**) to increase respective discharge rates of batteries **110**(**2**) and **110**(**3**) at time t.sub.1 by ΔDR.sub.a/2 to compensate for the decrease in discharge rate of battery **110**(**1**), thereby maintaining constant V.sub.bus and power provided by stack **1704**.
(53) Additionally, FIG. **18** is a schematic diagram of stack **1704** illustrating an example of how battery management controller **102** might adjust battery discharge rate to compensate for decrease in discharge rate of battery **110**(**3**) at time t.sub.2. In this example, battery management controller **102** controls power converter **112**(**3**) to decrease discharge rate of battery **110**(**3**) by ΔDR.sub.b at time t.sub.2 to allow SOC of battery **110**(**2**) to catch up to SOC of batteries **110**(**1**) and **110**(**3**). Battery management controller **102** also controls power converter **112**(**2**) to increase rate of discharge of battery **110**(**2**) by ΔDR.sub.b to compensate for the decrease in discharge rate of battery **110**(**3**), thereby maintaining constant V.sub.bus and power provided by stack **1704**.
(54) In some embodiments, battery management controller **102** is further configured to adapt charge and discharge rates of batteries **110** in stack **104** so that all batteries reach a threshold value, corresponding to a knee of battery voltage versus SOC curve or a battery voltage versus time curve, at substantially the same time. For example, referring again to FIG. **13**, a difference in time between when the first battery **110** reaches the threshold value and when the second battery reaches the threshold value is Δt.sub.1, and a difference in time between when the first battery **110** reaches the threshold value and when the third battery reaches the threshold value is Δt.sub.2. Additionally, a difference in time between when the second battery **110** reaches the threshold value and when the third battery reaches the threshold value is Δt.sub.3. Some embodiments of battery management controller **102** are configured to adjust the respective charge rates of one or more of the first through third batteries **110** to minimize each of Δt.sub.1, Δt.sub.2, and Δt.sub.3, so that all three batteries reach the threshold value at substantially the same time. For example, in response to the first battery **110** reaching the threshold value before the second and third batteries **110**, battery management controller **102** may decrease the charge rate of the first battery **110** and/or increase the charge rates of the second and third batteries **110** in future charge cycles, to decrease each of Δt.sub.1, Δt.sub.2, and Δt.sub.3 over one or more cycles.
(55) In some embodiments, battery management controller **102** is configured to use an iterative process to minimize each of Δt.sub.1, Δt.sub.2, and Δt.sub.3, such as by repeatedly (a) changing a battery charge rate, (b) evaluating an effect of the charge rate change on one or more of Δt.sub.1, Δt.sub.2, and Δt.sub.3, and (c) changing the battery charge rate in the same direction, if the previous change in charge rate decreased Δt.sub.1, Δt.sub.2, and/or Δt.sub.3, and changing the battery charge rate in the opposite direction, if the previous change in charge rate increased Δt.sub.1, Δt.sub.2, and/or Δt.sub.3. Battery management controller **102** may continue this process, for example, until each of Δt.sub.1, Δt.sub.2, and Δt.sub.3 reaches a predetermined minimum value. Additionally, some embodiments of battery management controller **102** are configured to at least partially use historical data from other energy storage systems, such specified in aggregate data **722** of FIG. **7**, to determine how to adjust battery charge rate to minimize Δt.sub.1, Δt.sub.2, and Δt.sub.3. Furthermore, certain embodiments of battery management controller **102** are configured to use artificial intelligence or machine learning, optionally in conjunction with aggregate data **722** of FIG. **7**, to determine how to adjust battery charge rate to minimize Δt.sub.1,

Δt.sub.2, and Δt.sub.3.

(56) Referring again to FIG. **16**, a difference in time between when the first battery **110** reaches the threshold value and when the third battery **110** reaches the threshold value is Δt.sub.1, and a difference in time between when the first battery **110** reaches the threshold value and when the second battery **110** reaches the threshold value is Δt.sub.2. Additionally, a difference in time between when the third battery **110** reaches the threshold value and when the second battery **110** reaches the threshold value is Δt.sub.3. Some embodiments of battery management controller **102** are configured to adjust the respective discharge rates of one or more of the first through third batteries **110** to minimize each of Δt.sub.1, Δt.sub.2, and Δt.sub.3, so that all three batteries reach the threshold value at substantially the same time. For example, some embodiments of battery management controller **102** are configured to minimize each of Δt.sub.1, Δt.sub.2, and Δt.sub.3 using one or more of the techniques discussed above with respect to FIG. **13**, but by adjusting discharge rate instead of charge rate.

(57) Furthermore, some embodiments of battery management controller **102** are configured to use feedback signals F from operation in both high SOC regions and low SOC regions to adjust charge and/or discharge rates so that all batteries **110** reach threshold values at substantially the same time. For example, battery management controller **102** may adjust discharge rate of a first battery **110** in response to the first battery **110** transitioning to a dead band region from a high SOC region at a different time than when a second battery **110** transitions from the high SOC region to the dead band region, to cause both batteries to transition to a low SOC region from the dead band region at substantially the same time. For instance, if the first battery **110** transitions to the dead band region from the high SOC region before the second battery **110**, battery management controller **102** may reduce discharge rate of the first battery **110** relative to the second battery **110**, so that the two batteries subsequently transition to the low SOC region from the dead band region at substantially the same time. Battery management control **102** may be configured to adjust battery **110** discharge rates using an iterative method and/or a machine learning method so that all batteries **110** transition between a dead band region and a low SOC region at substantially the same time.

(58) Additionally, battery management controller **102** may adjust a charge rate of a first battery **110** in response to the first battery **110** transitioning to a dead band region from a low SOC region at a different time than when a second battery **110** transitions from the low SOC region to the dead band region, to cause both batteries to transition to a high SOC region from the dead band region at substantially the same time. For instance, if a first battery **110** enters the dead band region from the low SOC region before a second battery **110**, battery management controller **102** may reduce charge rate of the first battery **110** relative to the second battery **110**, so that the two batteries subsequently enter the high SOC region from the dead band region at substantially the same time. Battery management control **102** may be configured to adjust battery **110** charge rates using an iterative method and/or a machine learning method so that all batteries **110** transition between a dead band region and a high SOC region at substantially the same time.

(59) Alternately or additionally, battery management controller **102** may be configured to account for variations in endpoint SOC values of batteries **110** when determining charge and/or discharge rates, so that all batteries **110** transition between a dead band region and a high or low SOC region at substantially the same time. For example, consider a hypothetical scenario where a first battery **110** is at a higher SOC than a second battery **110** at an end of a charge cycle. Battery management controller **102** may be configured to increase a discharge rate of the first battery **110** relative to the second battery **110** to compensate for the difference in SOC of the two batteries at the end of the charge cycle, so that both batteries **110** transition from a dead band region to a low SOC region at substantially the same time during discharging. As another example, consider a hypothetical scenario where a first battery **110** is at a lower SOC than a second battery **110** at an end of a discharge cycle. Battery management controller **102** may be configured to increase a charge rate of the first battery **110** relative to the second battery **110** to compensate for the difference in SOC of

the two batteries at the end of the discharge cycle, so that both batteries **110** transition from the dead band region to a high SOC region at substantially the same time during charging. Battery management controller **102** may be configured to use an iterative method and/or a machine learning method to determine required adjustments to battery **110** charge and/or discharge rates to compensate for variations in endpoint SOC values of batteries **110**. Battery management controller **102** may be further configured to determine SOC from battery **110** voltage during rest periods at the beginning and end of charge and discharge cycles. A battery **110** is not charged or discharged during a rest cycle, and measured battery voltage during a rest cycle therefore represents true open circuit voltage of the battery. Accordingly, it may be advantageous to measure battery **110** voltage during a rest cycle, when feasible, to obtain battery open circuit voltage and eliminate need for estimating open circuit voltage.

(60) FIG. **19** is a flow chart of a method **1900** for managing a plurality of batteries that are electrically coupled together, to mitigate effects of dead band operation on battery SOC balancing. In a block **1902** of method **1900**, respective voltages of the plurality of batteries are monitored. In one example of block **1902**, battery management controller **102** monitors respective voltages V.sub.bat of batteries **110**, respective estimated open circuit voltages V.sub.oc_est of batteries **110**, or respective actual open circuit voltages V.sub.oc, at least partially based on feedback signals F. In a block **1904** of method **1900**, a charge or discharge rate of a first battery of the plurality of batteries is reduced, relative to at least a second battery of the plurality of batteries, in response to a respective voltage of first battery reaching a first threshold value at a first time. In one example of block **1904**, charge rate of the first battery discussed in FIG. **13** is reduced, in response to voltage of the first battery reaching the threshold value at time t.sub.1, and a charge rate of one or more other batteries is optionally increased to compensate for the reduction in charge rate of the first battery. In another example of block **1904**, discharge rate of the first battery discussed in FIG. **16** is reduced, in response to voltage of the first battery reaching the threshold value at time t.sub.1, and a discharge rate of one or more other batteries is optionally increased to compensate for the reduction in discharge rate of the first battery.

(61) In a block **1906** of method **1900**, the respective charge or discharge rate of the first battery is increased at a second time that is after the first time, in response to a respective voltage of the second battery reaching the first threshold value. In one example of block **1906**, charge rate of the first battery discussed in FIG. **13** is increased, in response to voltage of the third battery reaching the threshold value at time t.sub.3. In another example of block **1906**, discharge rate of the first battery discussed in FIG. **16** is increased, in response to voltage of the second battery reaching the threshold value at time t.sub.3.

(62) Changes may be made in the above methods, devices, and systems without departing from the scope hereof. It should thus be noted that the matter contained in the above description and shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover generic and specific features described herein, as well as all statements of the scope of the present method and system, which as a matter of language, might be said to fall therebetween.

Claims

1. A method for managing a plurality of batteries that are electrically coupled together, the method comprising: (a) monitoring respective voltages of the plurality of batteries; (b) in response to a respective voltage of a first battery of the plurality of batteries reaching a first threshold value at a first time, reducing a charge or discharge rate of the first battery relative to at least a second battery of the plurality of batteries at least partially by changing operation of a first power converter electrically coupled to the first battery independently of operation of a second power converter electrically coupled to the second battery; and (c) after step (b), adaptively managing charge or

discharge rates of the plurality of batteries to reduce a difference in time between when (i) the respective voltage of the first battery reaches the first threshold value and (ii) a respective voltage of the second battery reaches the first threshold value.

2. The method of claim 1, where the first and second power converters are electrically coupled in series.

3. The method of claim 1, further comprising increasing a charge or discharge rate of the second battery to compensate for reducing the charge or discharge rate of the first battery.

4. The method of claim 3, wherein increasing the charge or discharge rate of the second battery comprises changing operation of the second power converter electrically coupled to the second battery.

5. The method of claim 1, further comprising increasing the respective charge or discharge rate of the first battery in response to a respective voltage of the second battery reaching the first threshold value at a second time that is after the first time.

6. The method of claim 1, wherein adaptively managing charge or discharge rates of the plurality of batteries comprises changing a charge or discharge rate of the first battery relative to the second battery.

7. The method of claim 1, wherein adaptively managing charge or discharge rates of the plurality of batteries comprises changing a charge or discharge rate of the second battery relative to the first battery.

8. The method of claim 1, wherein adaptively managing charge or discharge rates of the plurality of batteries comprises using an iterative process to reduce the difference in time between when (i) the respective voltage of the first battery reaches the first threshold value and (ii) the respective voltage of the second battery reaches the first threshold value.

9. The method of claim 1, wherein the respective voltages of the plurality of batteries comprise one of (a) actual battery voltages, (b) actual battery open circuit voltages, and (c) estimated battery open circuit voltages.

10. The method of claim 1, wherein the first threshold value corresponds to one of (a) a knee in a battery voltage versus state of charge curve and (b) a knee in a battery voltage versus time curve.

11. The method of claim 1, wherein the first threshold value corresponds to one of (a) a predetermined change in the respective voltage of the first battery and (b) a predetermined rate of change in the respective voltage of the first battery.

12. The method of claim 1, wherein each battery is a battery module comprising either (a) a plurality of electrochemical cells or (b) a single electrochemical cell.

13. The method of claim 1, further comprising adaptively managing charge or discharge rates of the plurality of batteries to reduce a difference in time between when (i) the respective voltage of the first battery reaches the first threshold value and (ii) a respective voltage of a third battery of the plurality of batteries reaches the first threshold value.

14. A method for managing a plurality of batteries that are electrically coupled together, the method comprising: (a) monitoring respective voltages of the plurality of batteries; (b) in response to a respective voltage of a first battery of the plurality of batteries reaching a first threshold value at a first time, reducing a charge or discharge rate of the first battery relative to at least a second battery of the plurality of batteries; and (c) after step (b), adaptively managing charge or discharge rates of the plurality of batteries at least partially by using historical data from an energy storage system to determine how to adjust a charge or discharge rate of one or more of the plurality of batteries, to reduce a difference in time between when (i) the respective voltage of the first battery reaches the first threshold value and (ii) the respective voltage of the second battery reaches the first threshold value.

15. A controller for managing a plurality of batteries that are electrically coupled together, comprising: one or more memories; and one or more processors communicatively coupled to the one or more memories, the one or more processors being configured to execute instructions stored

in the one or more memories to: monitor respective voltages of the plurality of batteries, in response to a respective voltage of a first battery of the plurality of batteries reaching a first threshold value at a first time, reduce a charge or discharge rate of the first battery, relative to at least a second battery of the plurality of batteries, and adaptively managing charge or discharge rates of the plurality of batteries, at least partially by using historical data from an energy storage system, to reduce a difference in time between when (i) the respective voltage of the first battery reaches the first threshold value and (ii) a respective voltage of the second battery reaches the first threshold value.

16. The controller of claim 15, wherein the one or more processors are further configured to execute instructions stored in the one or more memories to increase a charge or discharge rate of the second battery to compensate for reducing the charge or discharge rate of the first battery.

17. The controller of claim 15, wherein the one or more processors are further configured to execute instructions stored in the one or more memories to increase the respective charge or discharge rate of the first battery, in response to a respective voltage of the second battery reaching the first threshold value at a second time that is after the first time.

18. The controller of claim 15, wherein the one or more processors are further configured to execute instructions stored in the one or more memories to adaptively managing charge or discharge rates of the plurality of batteries to reduce a difference in time between when (i) the respective voltage of the first battery reaches the first threshold value and (ii) a respective voltage of a third battery of the plurality of batteries reaches the first threshold value.