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(54) **BATTERY MANAGEMENT CONTROLLERS AND ASSOCIATED METHODS**

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(57) **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.
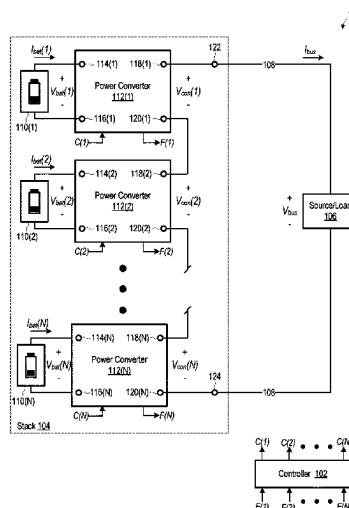
18 Claims, 16 Drawing Sheets

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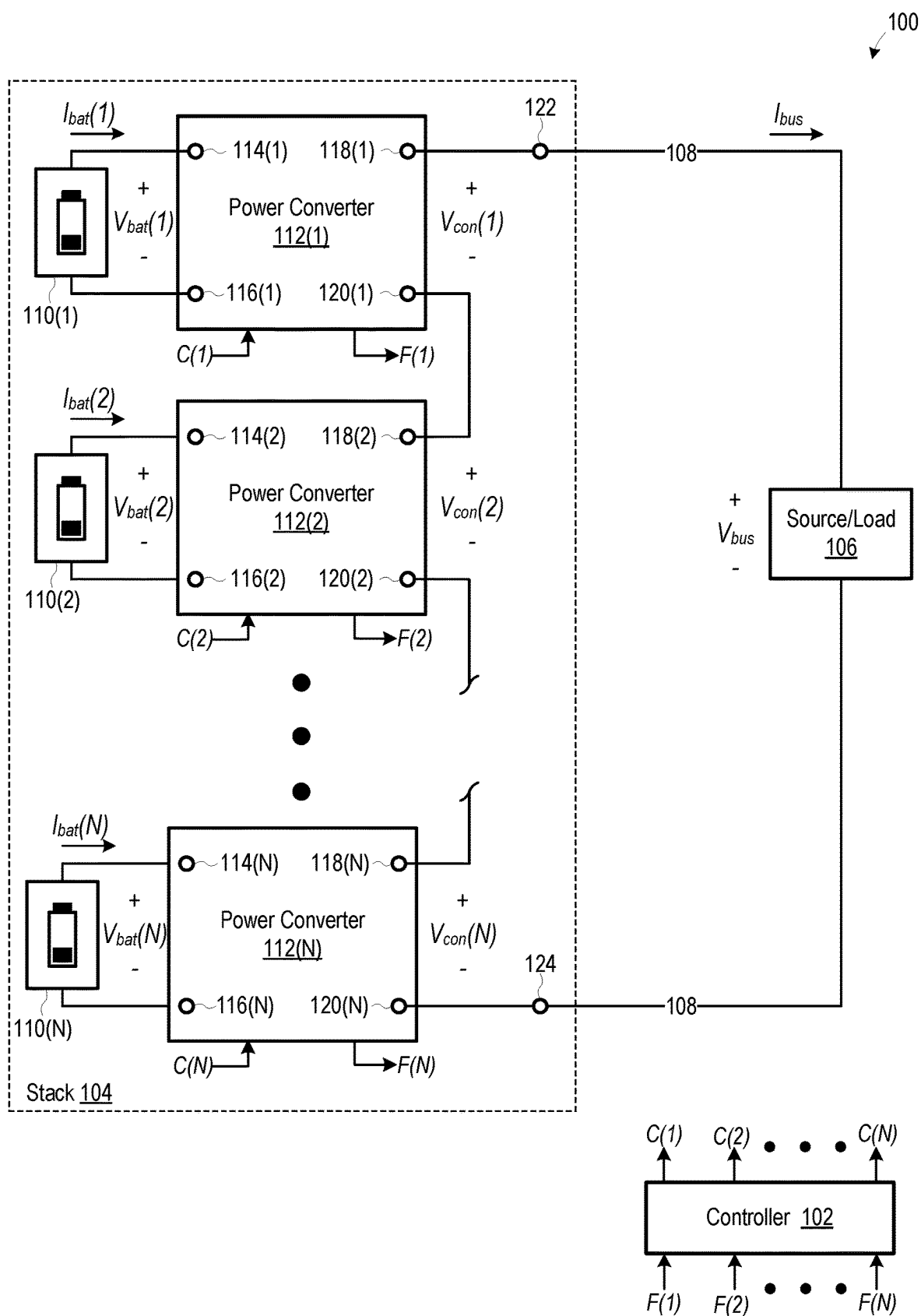
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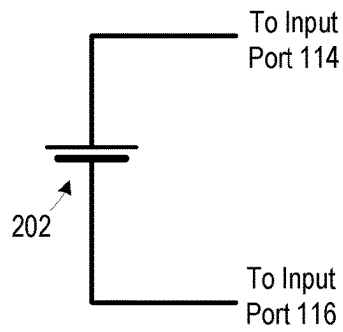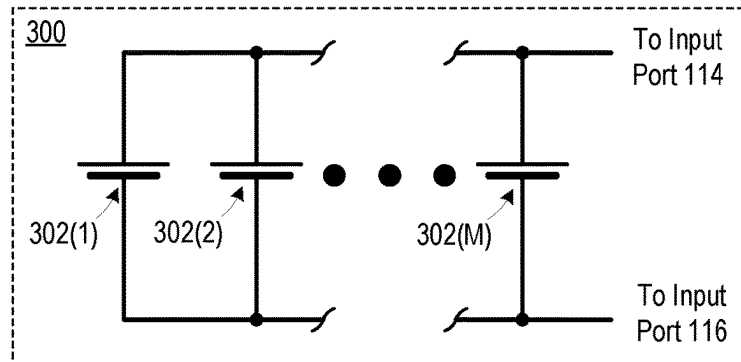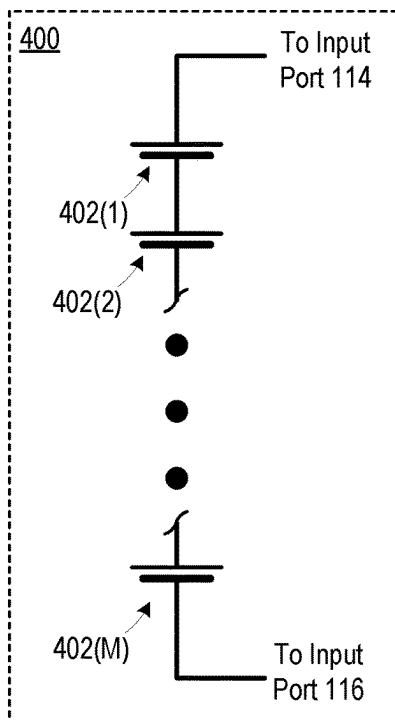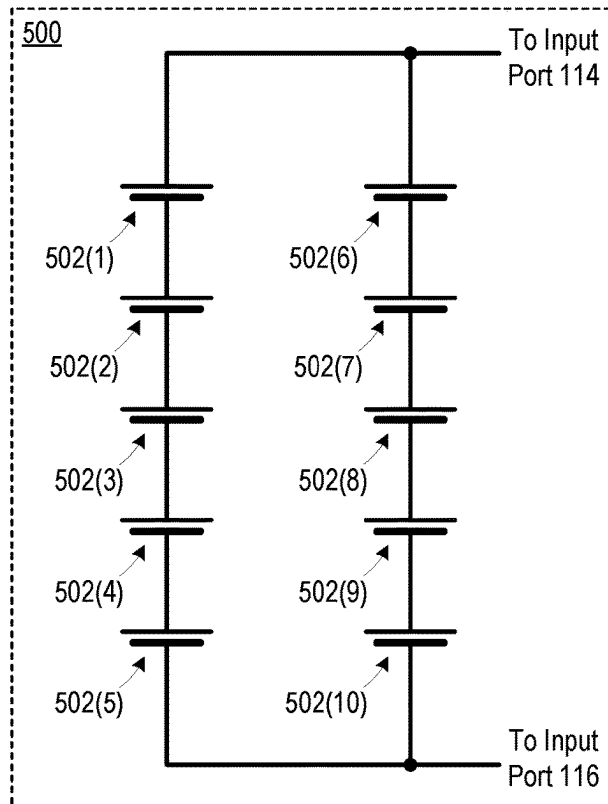
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FIG. 1

To Input
Port 114

202

To Input
Port 116

FIG. 2

300

302(1)   302(2)   ● ● ●   302(M)

To Input
Port 114

To Input
Port 116

FIG. 3

400

402(1)

402(2)

●
●
●

402(M)

To Input
Port 114

To Input
Port 116

FIG. 4

500

502(1)   502(6)

502(2)   502(7)

502(3)   502(8)

502(4)   502(9)

502(5)   502(10)

To Input
Port 114

To Input
Port 116

FIG. 5

600

$C(1)$ $C(2)$ • • • $C(N)$ $F(1)$ $F(2)$ • • • $F(N)$

Interface Circuitry
606

Processor
602

Instructions
608

Memory 604

FIG. 6

700

Global Processor
710

Global Memory 712

Global Instructions
718

Aggregate Data
722

720

716

Networks/Internet
714

720

716

System Processor
702

System Memory 704

System
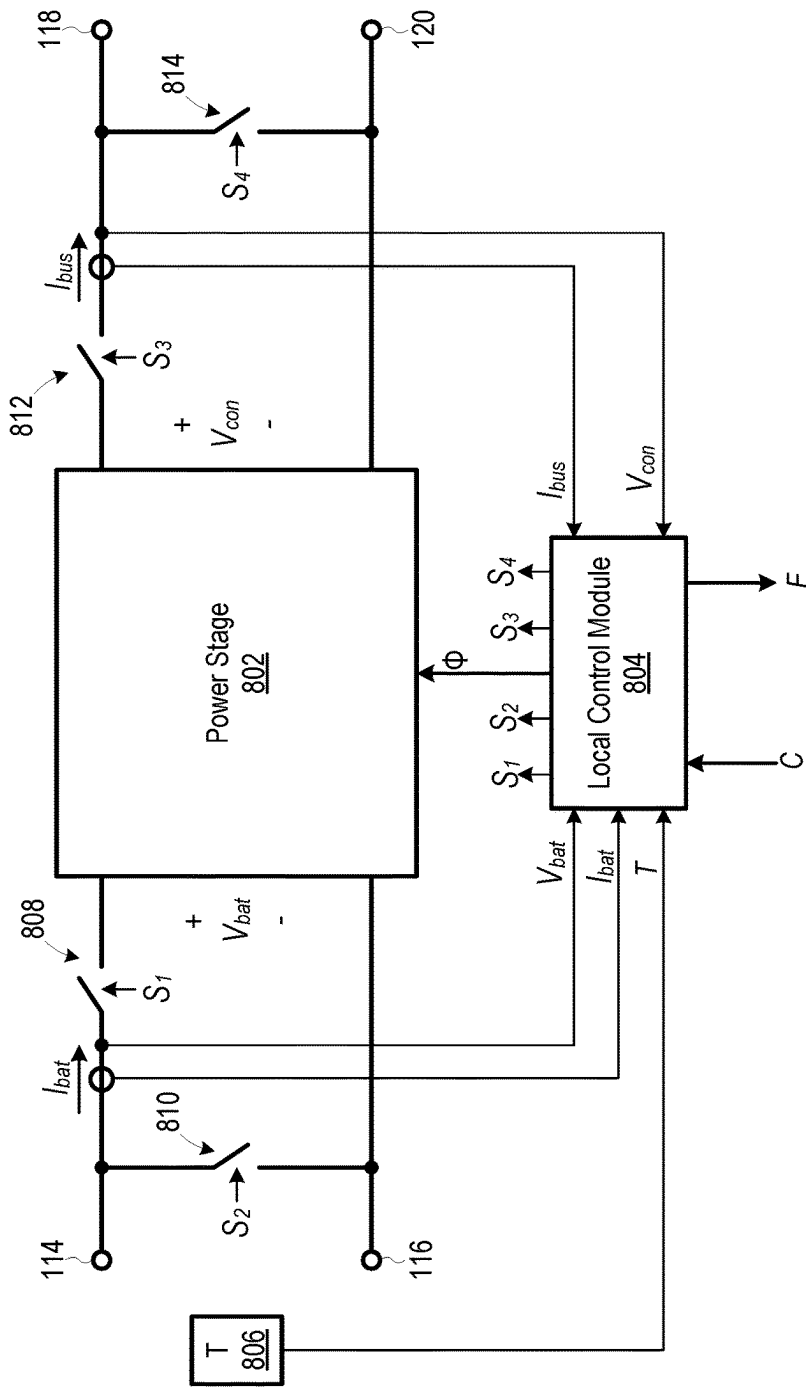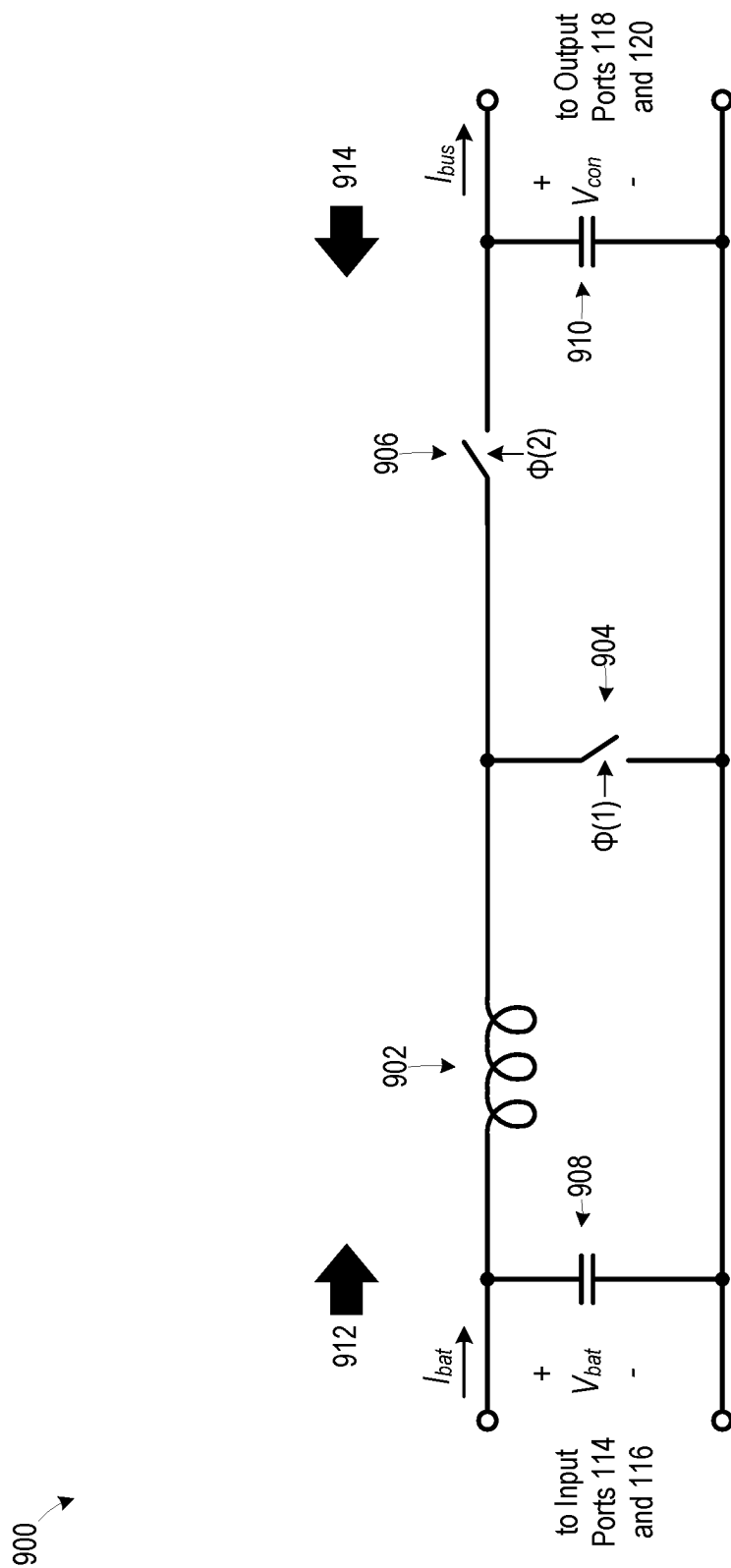Instructions
708
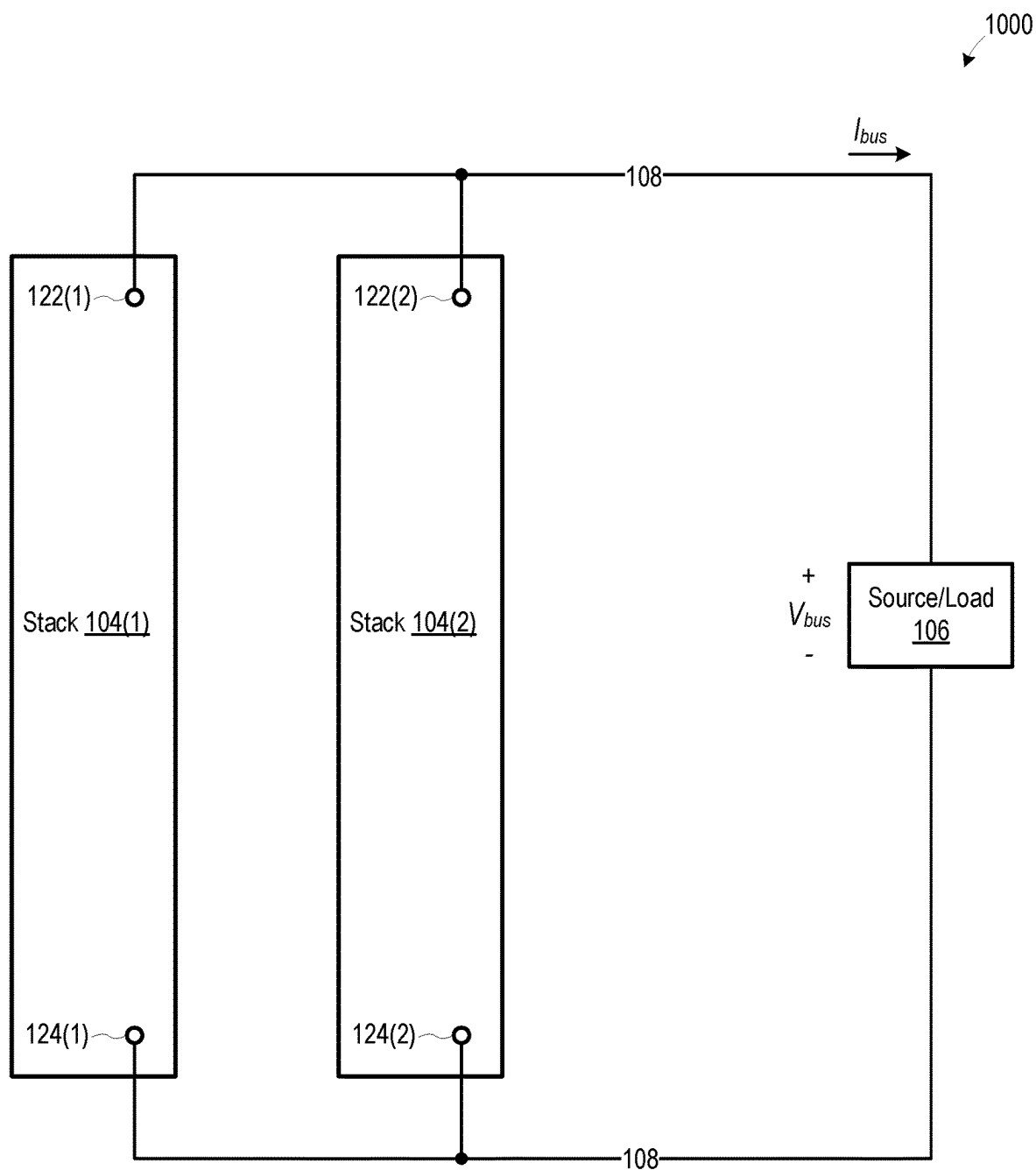
Interface Circuitry
706

C(1)   C(2)   • • •   C(N)   F(1)   F(2)   • • •   F(N)

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

$[-\Delta CR_a]$

$[+\Delta CR_a/2]$

$[+\Delta CR_a/2]$

$I_{bat}(1)$

I_{bus} 122

114(1)   118(1)   108

+
$V_{bat}(1)$
-

Power Converter
112(1)

+
$V_{con}(1)$
-

116(1)   120(1)

110(1)

C(1)   F(1)

$I_{bat}(2)$

114(2)   118(2)

+
$V_{bat}(2)$
-

Power Converter
112(2)

+
$V_{con}(2)$
-

+
V_{bus}
-

116(2)   120(2)

110(2)

C(2)   F(2)

$I_{bat}(3)$

114(3)   118(3)

+
$V_{bat}(3)$
-

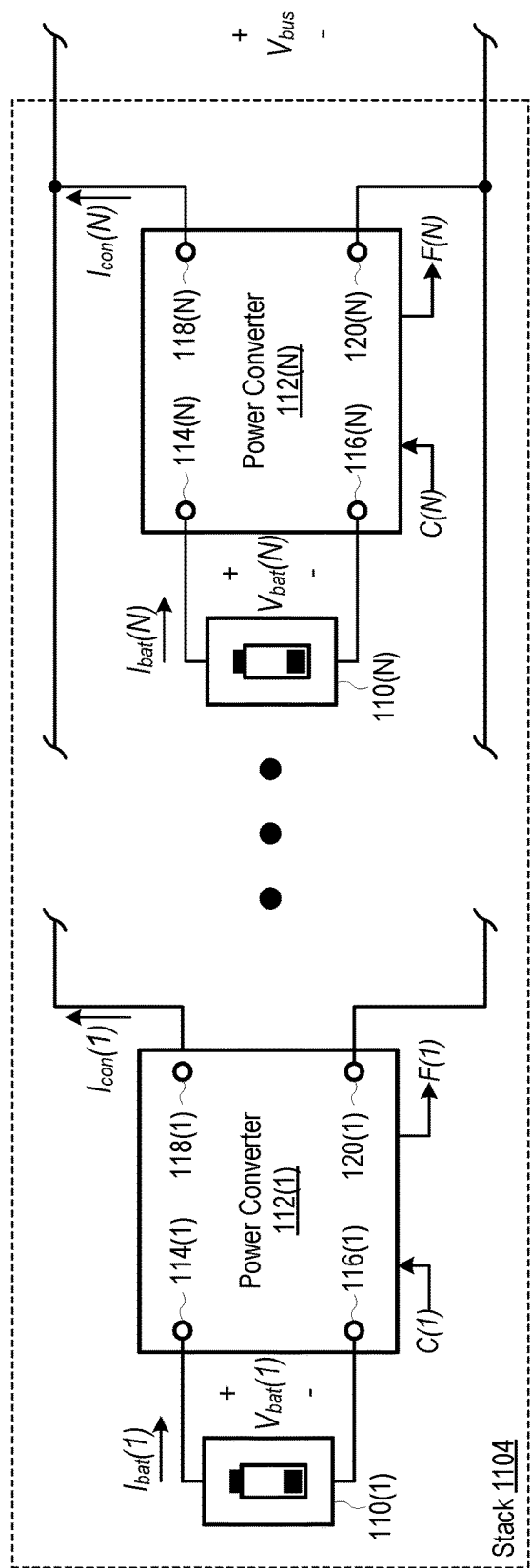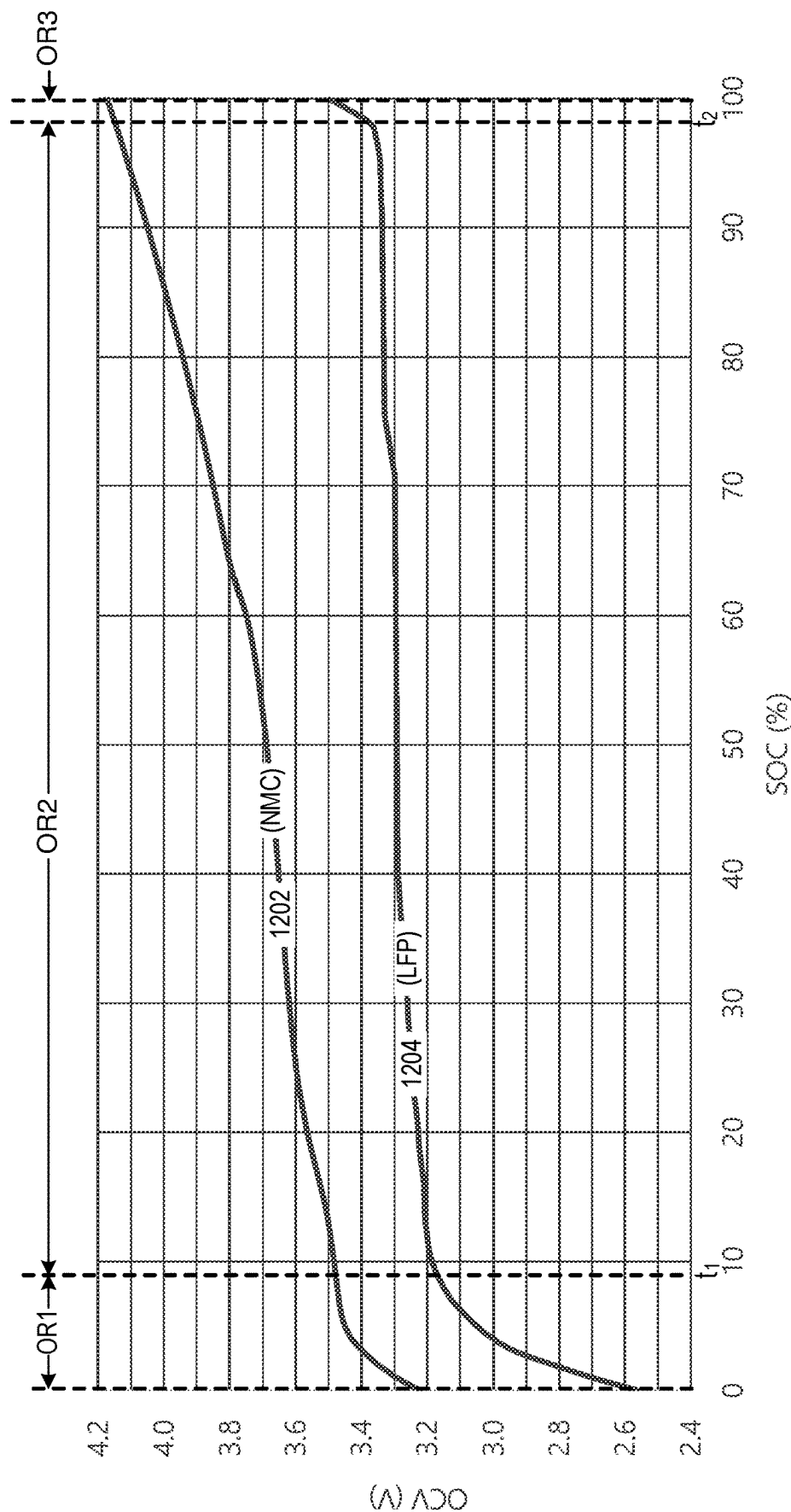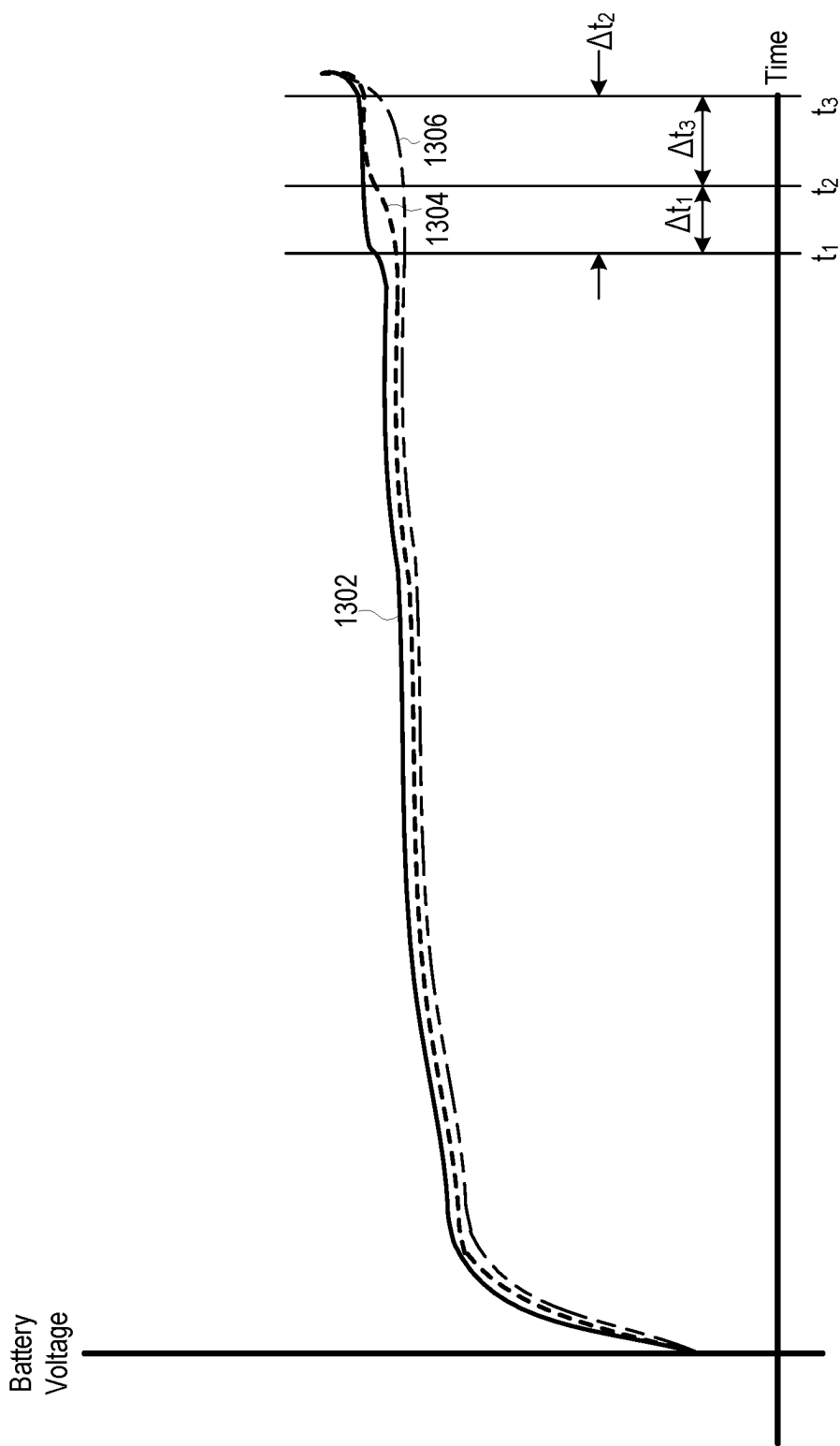Power Converter
112(3)
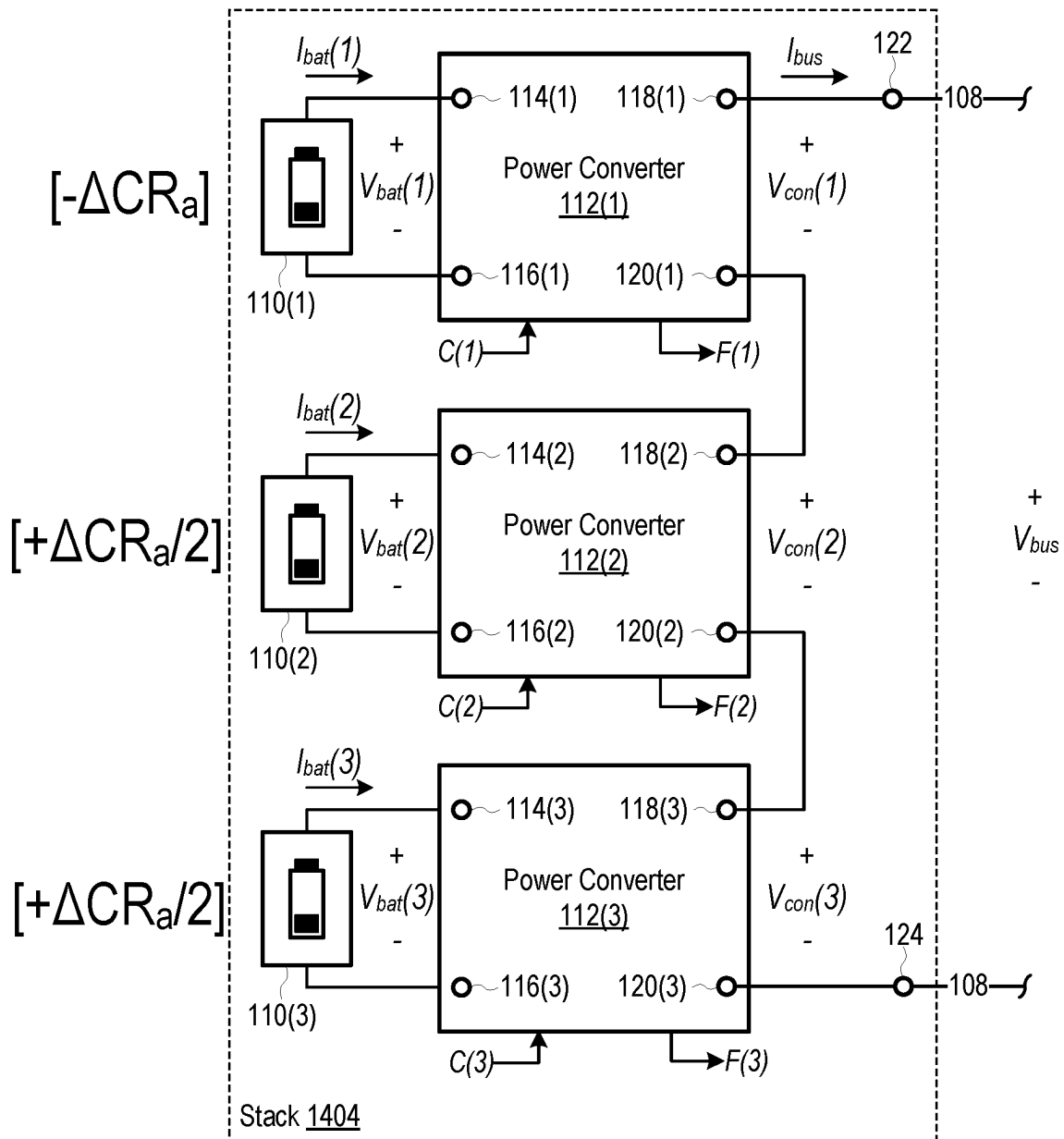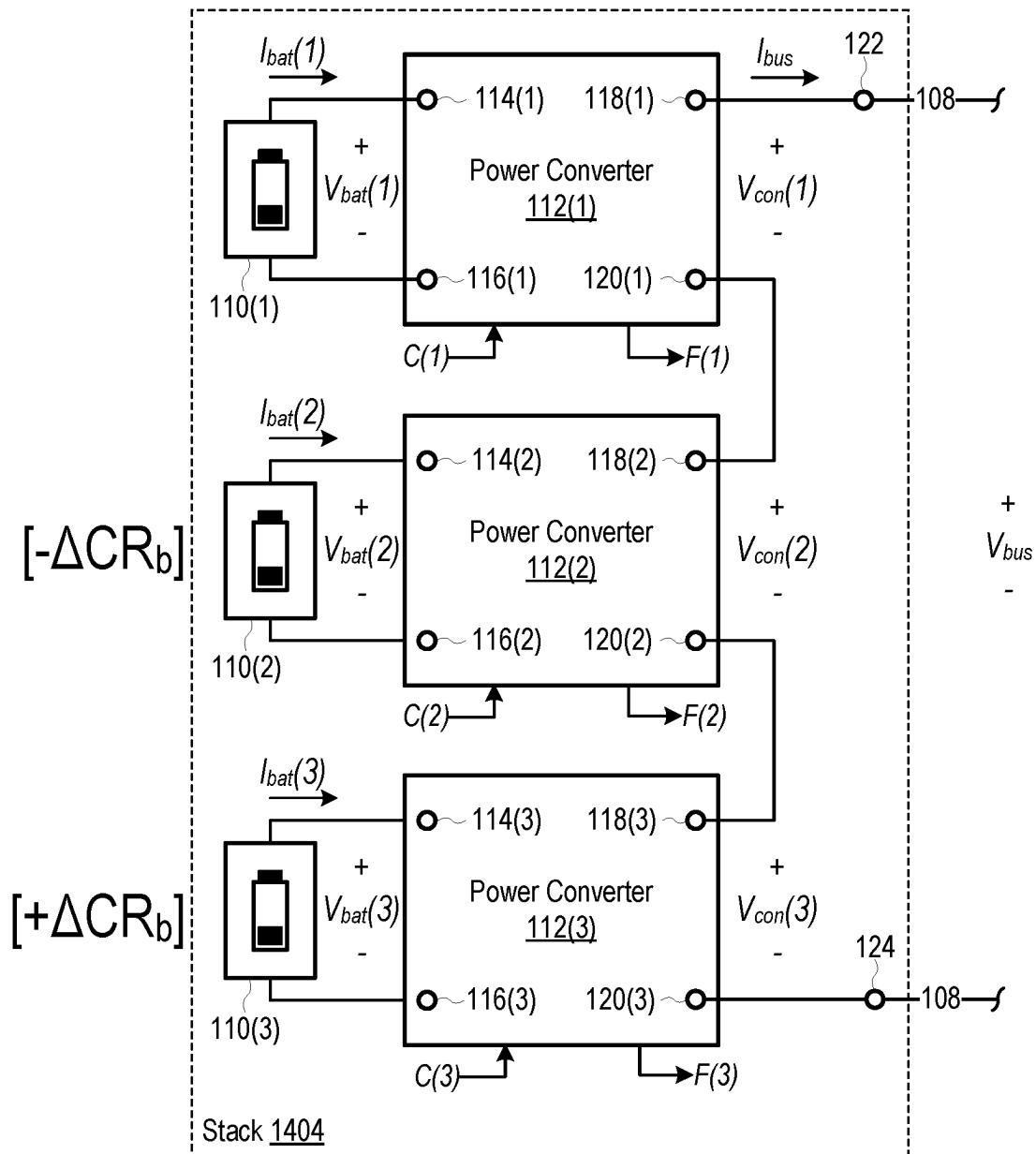
+
$V_{con}(3)$
-

124

116(3)   120(3)   108

110(3)

C(3)   F(3)

Stack 1404

FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18

1900

Monitor Respective Voltages of a Plurality of Batteries

1902

In Response to a Respective Voltage of a First Battery of the Plurality of Batteries Reaching a 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

1904

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, Increasing the Respective Charge or Discharge Rate of the First Battery
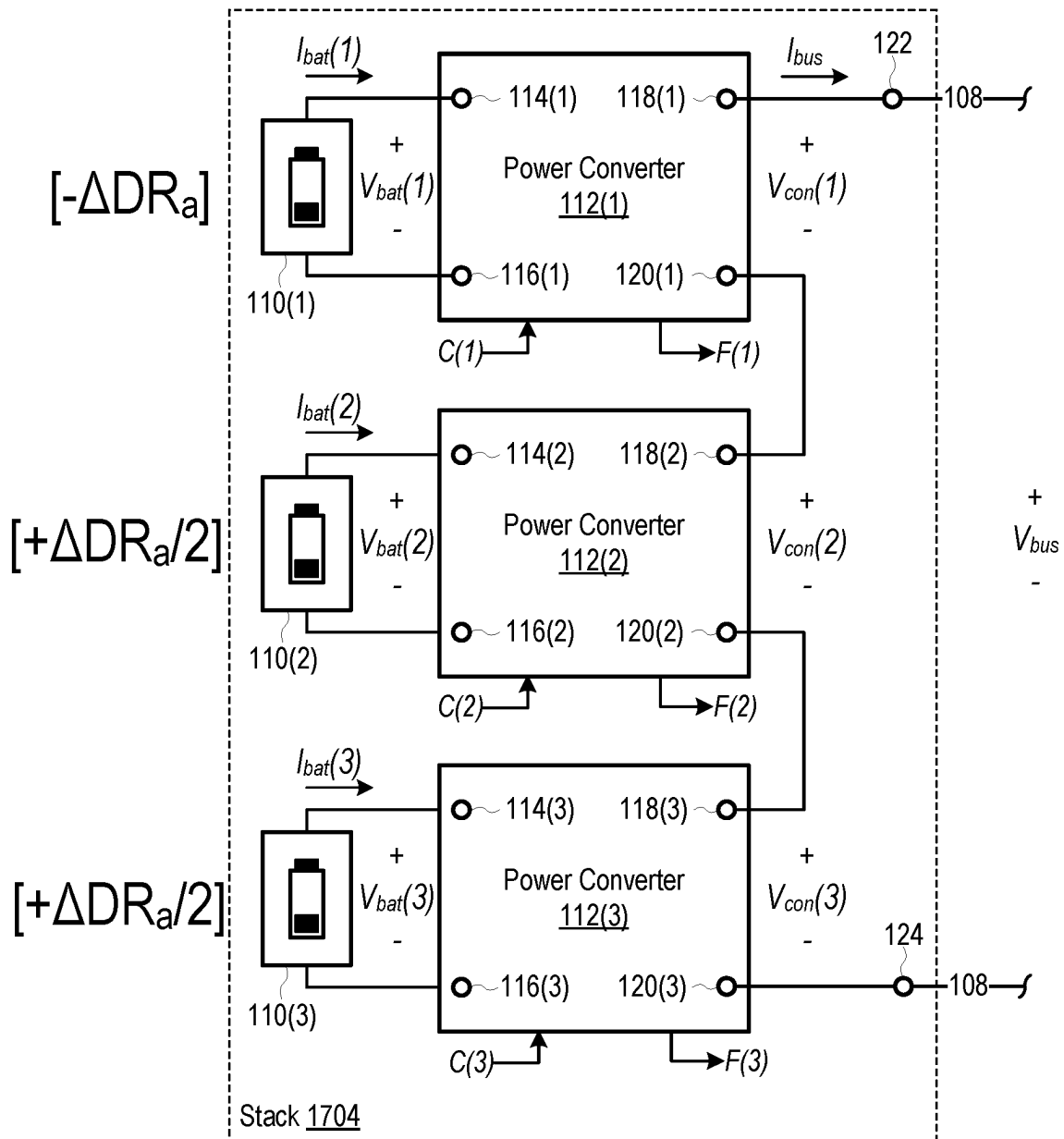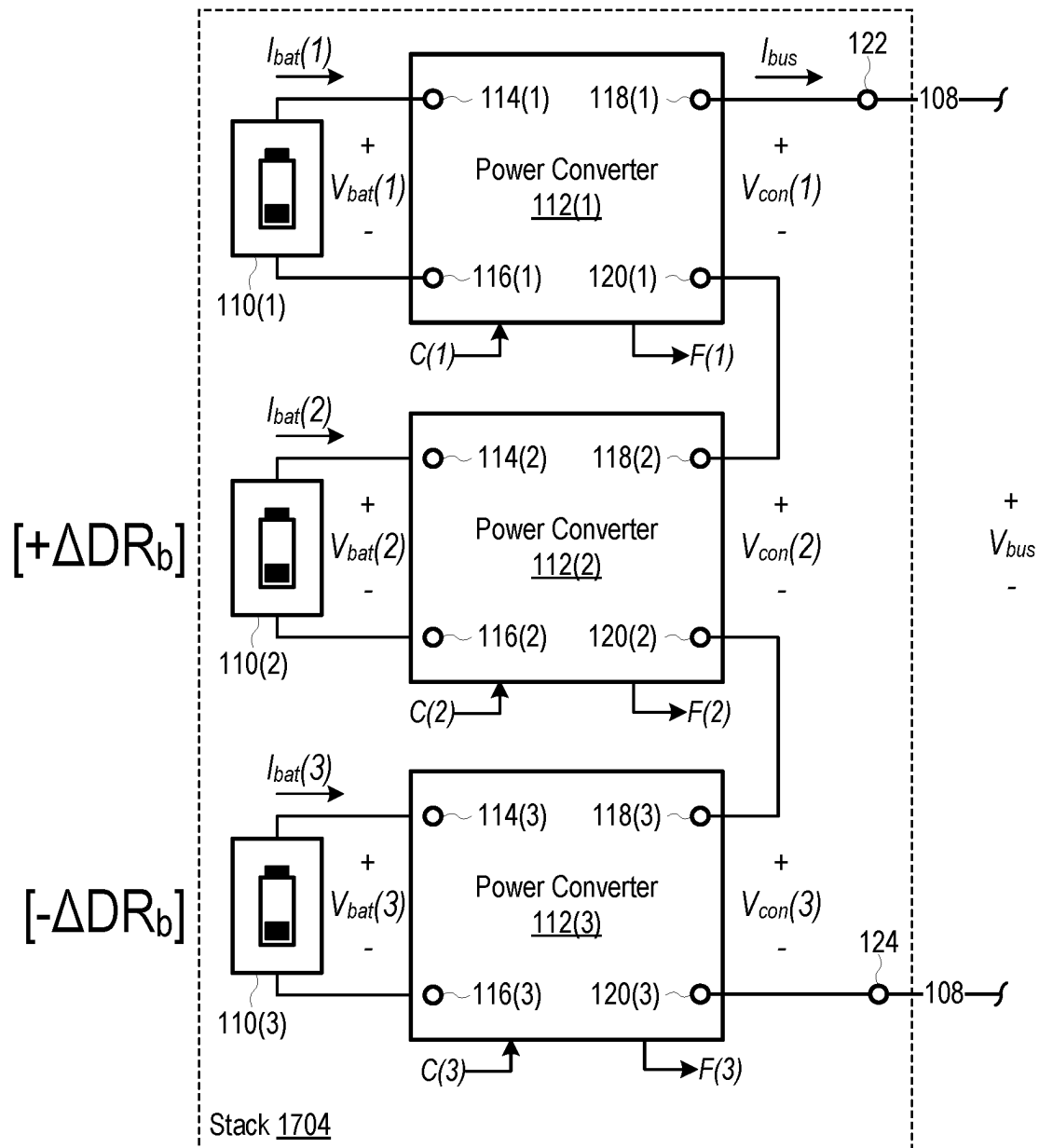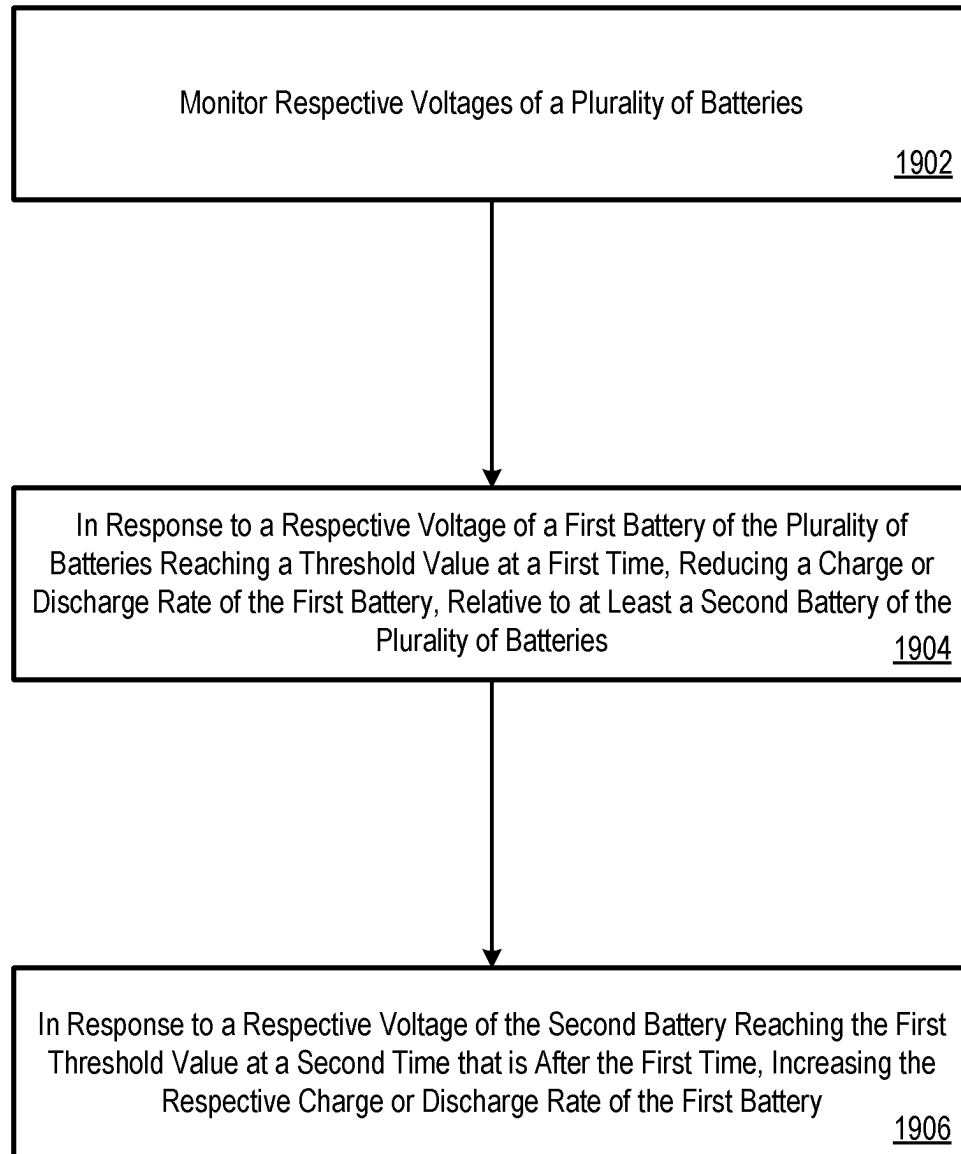
1906

FIG. 19

BATTERY MANAGEMENT CONTROLLERS AND ASSOCIATED METHODS

RELATED APPLICATIONS

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

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 a 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.

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.

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.

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

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.

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.

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

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of an energy storage system including a stack of batteries and power converters, according to an embodiment.

FIG. 2 is a schematic diagram of a battery that is a single electrochemical cell.

FIG. 3 is a schematic diagram of a battery including a plurality of electrochemical cells electrically coupled in parallel.

FIG. 4 is a schematic diagram of a battery including a plurality of electrochemical cells electrically coupled in series.

FIG. 5 is a schematic diagram of a battery including a plurality of electrochemical cells electrically coupled in a series/parallel combination.

FIG. 6 is a schematic diagram of one embodiment of a battery management controller of the FIG. 1 energy storage system.

FIG. 7 is a schematic diagram of another embodiment of a battery management controller of the FIG. 1 energy storage system.

FIG. 8 is a schematic diagram of one embodiment of a power converter of the FIG. 1 energy storage system.

FIG. 9 is a schematic diagram of one embodiment of a power stage of the FIG. 8 power converter.

FIG. 10 is a schematic diagram of an alternate embodiment of the FIG. 1 electric energy storage system including two stacks.

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.

FIG. 12 is a graph of open circuit voltage versus state of charge for two different battery types.

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.

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.

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

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.

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.

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.

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

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.

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.

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.

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.

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_{bat} across battery 110 (e.g., voltage across terminals of the battery), (b) current I_{bat} flowing through battery 110, (c) voltage V_{con} across the power converter 112's output ports 118 and 120, (d) current I_{bus} flowing through the power converter 112's output ports 118 and 120, and (e) temperature of battery 110.

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.

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**.

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**.

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.

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**.

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_{bat}, battery current I_{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**.

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**.

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**.

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**.

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.

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_{bat} across input ports 114 and 116 to voltage V_{con} across output ports 118 and 120, (b) transform voltage V_{con} across output ports 118 and 120 to voltage V_{bat} across input ports 114 and 116, (c) transform current I_{bat} flowing through battery 110 and input ports 114 and 116 to current I_{bus} flowing through output ports 118 and 120 and electric power bus 108, and (d) transform current I_{bus} flowing through output ports 118 and 120 and electric power bus 108 to current I_{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.

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 $\phi(1)$ and $\phi(2)$ generated by local control module 804 of FIG. 8. Magnitude of voltage V_{con} is greater than or equal to magnitude of voltage V_{bat} in power stage 900. Power stage 900 increases voltage magnitude from V_{bat} to V_{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.

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_{bat}, (c) current I_{bat}, (d) voltage V_{con}, and (e) current I_{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_1, S_2, S_3, and S_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_{bus} to bypass power stage 802.

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_{con} of each power converter 112, where bus contribution voltages V_{con} sum to bus voltage V_{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_{bus} flowing through power converter output ports 118 and 120.

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_{bus}, and/or electrical power flow between stacks **104** and source/load **106**, as well as among stacks **104(1)** and **104(2)**.

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_{con} across each power converter **112**'s output ports **118** and **120** is equal to voltage V_{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_{con} flowing through its output ports **118** and **120** to electric power bus **108**.

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_{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_{bat} at least partially by (1) determining each voltage V_{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_{bat} and an average voltage $V_{bat,avg}$ of all batteries **110**. For example, in certain embodiments, battery management controller **102** assigns a battery **110** with a smallest value of V_{bat} the most power during charging, and battery management controller **102** assigns a battery **110** with a largest value of V_{bat} the most power during discharging, to cause battery voltages V_{bat} to at least substantially converge during a charge or discharge cycle or over multiple charge or discharge cycles.

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 ($\Delta OCV/\Delta SOC$). 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_{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 thresh-

old 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.

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_1 and t_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_{bat}, estimated open circuit voltage V_{oc}, or actual open circuit voltage V_{oc}.

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_{bus} and/or power into or out of stack **104**.

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 $V_{bat}(1)$ of a first battery **110(1)** in stack **104**, curve **1304** corresponds to a voltage $V_{bat}(2)$ of a second battery **110(2)** in stack **104**, and curve **1306** corresponds to a voltage $V_{bat}(3)$ of a third battery **110(3)** in stack **104**. Voltages of the batteries **110** are, for example, either actual battery voltage V_{bat}, estimated open circuit voltage V_{oc}, or actual open circuit voltage V_{oc}. Voltage $V_{bat}(1)$ of first battery **110(1)** reaches a threshold value, corresponding to a predetermined change in battery voltage, at time t_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 $V_{bat}(2)$ of second battery 110(2) reaches the threshold value at time t_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 $V_{bat}(3)$ of third battery 110(3) reaches the threshold value at time t_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_3. Thus, battery management controller 102 approximately equalizes SOC of the three batteries 110 by time t_3.

Reducing charge rate of first battery 110(1) at time t_1 will change voltage V_{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_1, to compensate for the decrease in charge rate of battery 110(1) at time t_1, and thereby maintain constant voltage V_{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_2, to compensate for the decrease in charge rate of battery 110(2) at time t_2, and thereby maintain constant voltage V_{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.

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_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_a, at time t_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_1 by $\Delta CR_a/2$ to compensate for the decrease in charge rate of battery 110(1), thereby maintaining constant V_{bus} and power absorbed by stack 1404.

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_2. In this example, battery management controller 102 controls power converter 112(2) to decrease charge rate of battery 110(2) by ΔCR_b at time t_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_b to compensate for the decrease in charge rate of battery 110(2), thereby maintaining constant V_{bus} and power absorbed by stack 1404.

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 $\Delta 3CR_a/4$ at time t_1 and (b) control power converter 112(3) to increase charge rate of battery 110(3) by $\Delta CR_a/4$ at time t_1, to compensate

for decrease in charge rate of battery 110(1) ΔCR_a at time t_1, instead of implementing the method illustrated in FIG. 14.

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 $V_{bat}(1)$ of a first battery 110(1) in stack 104, curve 1604 corresponds to a voltage $V_{bat}(2)$ of a second battery 110(2) in stack 104, and curve 1606 corresponds to a voltage $V_{bat}(3)$ of a third battery 110(3) in stack 104. Voltages of the batteries 110 are, for example, either actual battery voltage V_{bat}, estimated open circuit voltage V_{oc}, or actual open circuit voltage V_{oc}. Voltage $V_{bat}(1)$ of first battery 110(1) reaches a threshold value, corresponding to a predetermined change in battery voltage, at time t_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 $V_{bat}(3)$ of third battery 110(3) reaches the threshold value at time t_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 $V_{bat}(2)$ of second battery 110(2) reaches the threshold value at time t_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_3. Thus, battery management controller 102 approximately equalizes SOC of the three batteries 110 by time t_3.

Reducing discharge rate of first battery 110(1) at time t_1 will change voltage V_{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_1, to compensate for the decrease in discharge rate of battery 110(1) at time t_1, and thereby maintain constant voltage V_{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_2, to compensate for the decrease in charge rate of battery 110(3) at time t_2, and thereby maintain constant voltage V_{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.

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_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_a, at time t_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_1 by $\Delta DR_a/2$ to compensate for

the decrease in discharge rate of battery 110(1), thereby maintaining constant V_{bus} and power provided by stack 1704.

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_2. In this example, battery management controller 102 controls power converter 112(3) to decrease discharge rate of battery 110(3) by ΔDR_b at time t_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_b to compensate for the decrease in discharge rate of battery 110(3), thereby maintaining constant V_{bus} and power provided by stack 1704.

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_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_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_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_1, Δt_2, and Δt_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_1, Δt_2, and Δt_3 over one or more cycles.

In some embodiments, battery management controller 102 is configured to use an iterative process to minimize each of Δt_1, Δt_2, and Δt_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_1, Δt_2, and Δt_3, and (c) changing the battery charge rate in the same direction, if the previous change in charge rate decreased Δt_1, Δt_2, and/or Δt_3, and changing the battery charge rate in the opposite direction, if the previous change in charge rate increased Δt_1, Δt_2, and/or Δt_3. Battery management controller 102 may continue this process, for example, until each of Δt_1, Δt_2, and Δt_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_1, Δt_2, and Δt_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_1, Δt_2, and Δt_3.

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_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_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_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_1, Δt_2, and Δt_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_1, Δt_2, and Δt_3 using one or more of the techniques discussed above with respect to FIG. 13, but by adjusting discharge rate instead of charge rate.

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.

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.

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.

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_{bat} of batteries **110**, respective estimated open circuit voltages V_{oc_est} of batteries **110**, or respective actual open circuit voltages V_{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_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_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.

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_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_3.

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.

What is claimed is:

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.

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