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United States Patent Application Publication	20250256620
Kind Code	A1
Publication Date	August 14, 2025
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SYSTEMS AND METHODS FOR BALANCING STATE OF CHARGES OF BATTERY MODULES

Abstract

A system for a vehicle includes a first battery module having a first capacity, a second battery module having a second capacity different than the first capacity, a DC-DC converter coupled to the first battery module and the second battery module, and a control module coupled to the DC-DC converter. The control module is configured to sense a first parameter associated with the first battery module and a second parameter associated with the second battery module, and control the DC-DC converter based on the first parameter and the second parameter to balance a state of charge of the first battery module and a state of charge of the second battery module. Other example systems and methods for controlling DC-DC converters to balance state of charges of battery modules are also disclosed.

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Family ID: **96499284**

Appl. No.: **18/598174**

Filed: **March 07, 2024**

Foreign Application Priority Data

CN	202410176928.9	Feb. 08, 2024

Publication Classification

Int. Cl.: **B60L58/22** (20190101); **B60L58/20** (20190101); **H02J7/00** (20060101); **H02J7/34** (20060101)

U.S. Cl.:

CPC **B60L58/22** (20190201); **B60L58/20** (20190201); **H02J7/0016** (20130101); **H02J7/00714** (20200101); **H02J7/007182** (20200101); **H02J7/342** (20200101); B60L2210/10 (20130101); H02J2207/20 (20200101)

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of Chinese Patent Application No. 202410176928.9, filed on Feb. 8, 2024. The entire disclosure of the application referenced above is incorporated herein by reference.

INTRODUCTION

[0002] The information provided in this section is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

[0003] The present disclosure relates to systems and methods for balancing state of changes of battery modules.

[0004] Electric vehicles (EVs) such as battery electric vehicles (BEVs), hybrid vehicles, and/or fuel cell vehicles include one or more electric machines and a battery system including one or more battery cells. The battery cells can be arranged in battery modules including two or more battery cells and/or in battery packs including two or more battery modules. A power control system is used to control charging and/or discharging of the battery system from a utility, regenerative braking and/or acceleration during driving.

SUMMARY

[0005] A system for a vehicle includes a first battery module having a first capacity, a second battery module having a second capacity different than the first capacity, a DC-DC converter coupled to the first battery module and the second battery module, and a control module coupled to the DC-DC converter. The control module is configured to sense a first parameter associated with the first battery module and a second parameter associated with the second battery module, and control the DC-DC converter based on the first parameter and the second parameter to balance a state of charge of the first battery module and a state of charge of the second battery module.

[0006] In other features, the DC-DC converter includes a first power switch coupled in parallel with the first battery module, a second power switch coupled in parallel with the second battery module, and an inductor coupled between the first and second power switches and the first and second battery modules.

[0007] In other features, the control module is configured to sense a current flowing through the inductor, and control the DC-DC converter based on the sensed current, the first parameter and the second parameter to balance the state of charge of the first battery module and the state of charge of the second battery module.

[0008] In other features, the control module is configured to control a current flowing through the inductor to balance the state of charge of the first battery module and the state of charge of the second battery module.

[0009] In other features, the first capacity of the first battery module is greater than the second capacity of the second battery module.

[0010] In other features, the control module is configured to control the first power switch with a pulse width modulated control signal to discharge current from the first battery module to the second battery module via the inductor, when the control module is in a discharging mode in which the first battery module and the second battery module provide power a load.

[0011] In other features, the control module is configured to control the second power switch with a pulse width modulated control signal to discharge current from the second battery module to the first battery module via the inductor, when the control module is in a charging mode in which the first battery module and the second battery module are receiving power.

[0012] In other features, the DC-DC converter includes a first capacitor coupled in parallel with the first power switch, and a second capacitor coupled in parallel with the second power switch.

[0013] In other features, the first parameter is a voltage of the first battery module, and the second parameter is a voltage of the second battery module.

[0014] In other features, the first battery module includes a plurality of cells, the second battery module includes a plurality of cells, and a chemical composition of at least one cell of the first battery module is different than a chemical composition of at least one cell of the second battery module.

[0015] In other features, the at least one cell of the first battery module is a lithium-nickel-cobalt-manganese oxide (NMC) cell, and the at least one cell of the second battery module is a lithium ferrophosphate (LFP) cell.

[0016] In other features, the first battery module includes N cells, the second battery module includes M cells, and N and M are integers greater than zero, and N is different than M.

[0017] In other features, the first battery module includes a plurality of cells, the second battery module includes a plurality of cells, and at least one dimension of the first battery module is different than a corresponding dimension of the second battery module.

[0018] In other features, a vehicle comprising the system and at least one load coupled to the first battery module and the second battery module.

[0019] A method of controlling a DC-DC converter in a vehicle to balance a state of charge of a first battery module and a state of charge of a second battery module is disclosed. The DC-DC converter includes a first power switch coupled in parallel with the first battery module, a second power switch coupled in parallel with the second battery module, and an inductor coupled between the first and second power switches and the first and second battery modules. The first battery module has a first capacity, the second battery module has a second capacity different than the first capacity. The method includes sensing at least one first parameter associated with the first battery module and at least one second parameter associated with the second battery module, and controlling the first power switch or the second power switch based on the first parameter and the second parameter to balance the state of charge of the first battery module and the state of charge of the second battery module.

[0020] In other features, the first capacity of the first battery module is greater than the second capacity of the second battery module.

[0021] In other features, controlling the first power switch or the second power switch includes controlling the first power switch with a pulse width modulated control signal to discharge current from the first battery module to the second battery module via the inductor, when the first battery module and the second battery module are providing power a load.

[0022] In other features, controlling the first power switch or the second power switch includes controlling the second power switch with a pulse width modulated control signal to discharge current from the second battery module to the first battery module via the inductor, when the first battery module and the second battery module are receiving power.

[0023] In other features, the first battery module includes a plurality of cells, the second battery module includes a plurality of cells, and a chemical composition of at least one cell of the first battery module is different than a chemical composition of at least one cell of the second battery module.

[0024] In other features, the at least one cell of the first battery module is a lithium-nickel-cobalt-

manganese oxide (NMC) cell, and the at least one cell of the second battery module is a lithium ferrophosphate (LFP) cell.
[0025] In other features, the first battery module includes N cells, the second battery module includes M cells, and N and M are integers greater than zero, and N is different than M.
[0026] In other features, the first battery module includes a plurality of cells, the second battery module includes a plurality of cells, and at least one dimension of the first battery module is different than a corresponding dimension of the second battery module.
[0027] Further areas of applicability of the present disclosure will become apparent from the detailed description, the claims and the drawings. The detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0028] The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:
[0029] FIG. **1** is a block circuit diagram of an example power system for balancing state of charges of two battery modules having different capacities, according to the present disclosure;
[0030] FIG. **2** is an isometric view of a battery pack including multiple battery modules according to the present disclosure;
[0031] FIG. **3** is a side view of the battery pack of FIG. **2**;
[0032] FIG. **4** is a block circuit diagram of an example power system for balancing state of charges of two battery modules having different chemical compositions, according to the present disclosure;
[0033] FIG. **5** is a block circuit diagram of the power system of FIG. **1** including a control module, according to the present disclosure;
[0034] FIGS. **6-7** are block circuit diagrams of the power system of FIG. **1** showing current flow during a discharging mode, according to the present disclosure;
[0035] FIG. **8** shows graphs representing various current characteristics and control signals for the power system **100** of FIGS. **6-7**, according to the present disclosure;
[0036] FIGS. **9-10** are block circuit diagrams of the power system of FIG. **1** showing current flow during a charging mode, according to the present disclosure;
[0037] FIG. **11** shows graphs representing various current characteristics and control signals for the power system **100** of FIGS. **9-10**, according to the present disclosure;
[0038] FIG. **12** is a block circuit diagram of the control module of FIG. **5**, according to the present disclosure;
[0039] FIG. **13** shows graphs representing various current characteristics of the power system **100** of FIG. **1** during a discharging mode, according to the present disclosure;
[0040] FIG. **14** shows graphs representing various current characteristics of the power system **100** of FIG. **1** during a charging mode, according to the present disclosure;
[0041] FIG. **15** is a vehicle including a power system for balancing state of charges of two battery modules, according to the present disclosure; and
[0042] FIG. **16** is flowchart of an example control process for balancing state of charges of two battery modules, according to the present disclosure.
[0043] In the drawings, reference numbers may be reused to identify similar and/or identical elements.
DETAILED DESCRIPTION
[0044] A battery pack for an EV includes battery modules each having battery cells. The battery

pack is often designed to maximize energy associated with a rechargeable energy storage system (RESS) in the EV and to maximize available space in the EV. To do so, battery cells having different dimensions, chemical compositions, and/or capacities may be packed together into different regions to form the battery modules, and then the battery modules may be grouped together to form the battery pack. Due to the differing configurations of battery cells, some of the battery modules may have different capacities. This may result in unbalanced power usage and state of charges for the battery modules. In other words, the amount of energy (e.g., a percentage) available in each battery module at a given time may be different.

[0045] The power systems and methods according to the present disclosure utilize a unique DC-DC power converter to balance the state of charges of battery modules having different capacities and/or chemical compositions. In various embodiments, the unique DC-DC power converter includes an inductor and two power switches controlled to transfer current from one of the battery modules to another one of the battery modules via the inductor. In doing so, the amount of current transferred (e.g., passing through the inductor) may be controlled to balance the state of charges of the battery modules having different capacities and/or chemical compositions. As a result, a RESS may be designed with battery modules having different capacities and dimensions to maximize the usage of available space in the EV, while also meeting load demands in the EV.

[0046] Referring now to FIG. **1**, a schematic diagram of an example power system **100** for a RESS is presented. As shown in FIG. **1**, the power system **100** generally includes four battery modules **102**, **104**, **106**, **108** coupled to one or more components **110**, and a DC-DC converter **112** coupled to the battery modules **102**, **104**. In such examples, the component(s) **110** may represent one or more loads or charging sources (e.g., a utility and/or another external power source, regenerative braking and/or another internal power source, etc.) depending on whether the battery modules **102**, **104**, **106**, **108** are being discharged to power the load(s) or being charged from the charging source(s). Additionally, in the example of FIG. **1**, the battery modules **102**, **104** have different capacities. For example, in FIG. **1**, the battery module **102** has the highest capacity, the battery module **104** has the lowest capacity, and the battery modules **106**, **108** have the same capacities (e.g., depending on the design of the battery modules **102**, **104**).

[0047] Although the power system **100** is shown as including four battery modules, it should be appreciated that the power system **100** (and/or any other power system herein) may include more or less battery modules. Additionally, while not shown in FIG. **1**, the power system **100** includes a control module for controlling the DC-DC converter **112** based on sensed parameters to balance a state of charge (SOC) of the battery module **102** and a SOC of the battery module **104**.

[0048] In FIG. **1**, the DC-DC converter **112** is generally used for SOC balancing of the battery modules **102**, **104**, as further explained herein. In such examples, the DC-DC converter **112** does not provide power to or receive power from any component besides the battery modules **102**, **104**. For instance, the DC-DC converter **112** does not provide power to or receive power from the component(s) **110** (e.g., when functioning as a load or a charging source). As such, a rating of the DC-DC converter **112** may be determined solely by the SOC balancing requirements of the battery modules **102**, **104** over a drive cycle. For instance, the converter voltage may be determined based on a maximum voltage of the two connected battery modules **102**, **104** with different capacities. Additionally, the converter current may be determined based on a maximum balancing current over a drive cycle. For example, for an 800V/275 Ah battery pack including the battery modules **102**, **104**, **106**, **108**, the converter rating may be only 3 kW with a voltage rating of 200V and a current rating of **15**A.

[0049] As shown in FIG. **1**, the DC-DC converter **112** includes two power switches **114**, **116**, an inductor **118**, and optional capacitors **120**, **122**. In such examples, the capacitors **120**, **122** may function to filter ripple current generated by the inductor **118**. In various embodiments, the power switches **114**, **116** may be any suitable switching devices, such as bipolar transistors (e.g., insulated-gate bipolar transistors, etc.), field-effect transistors (e.g., metal-oxide-semiconductor field-effect transistors, etc.), wide-bandgap (WBG) switching devices, etc.

[0050] In this example, the power switches **114**, **116** are coupled in parallel with the battery modules **102**, **104** and the optional capacitors **120**, **122**, respectively. As such, the power switches **114**, **116** are coupled in parallel with the battery modules **102**, **104** having different capacities (e.g., the capacity of the battery module **102** is greater than the capacity of the battery module **104**).

[0051] Additionally, the inductor **118** and the capacitors **120**, **122** are coupled between the power switches **114**, **116** and the battery modules **102**, **104**. More specifically, the power switch **114** includes opposing terminals **124**, **130**, the capacitor **120** includes opposing terminals **126**, **132**, and the battery module **102** includes opposing terminals **128**, **134**. In this example, the terminals **124**, **126**, **128** of the power switch **114**, the capacitor **120**, and the battery module **102** are coupled together, and the terminals **132**, **134** of the capacitor **120** and the battery module **102** are coupled together. Similarly, the power switch **116** includes opposing terminals **136**, **142**, the capacitor **122** includes opposing terminals **138**, **144**, and the battery module **104** includes opposing terminals **140**, **146**. As shown, the terminals **130**, **136** of the power switches **114**, **116** are coupled together, the terminals **132**, **138** of the capacitors **120**, **122** are coupled together, and the terminals **134**, **140** of the battery modules **102**, **104** are coupled together. Additionally, the terminals **138**, **140** of the capacitor **122** and the battery module **104** are coupled together, and the terminals **142**, **144**, **146** of the power switch **116**, the capacitor **122**, and the battery module **104** are coupled together. In the example of FIG. **1**, the inductor **118** is coupled between the terminals **130**, **136** of the power switches **114**, **116**, and the terminals **134**, **140** of the battery modules **102**, **104** (and the terminals **132**, **138** of the capacitors **120**, **122**).

[0052] In various embodiments, the battery modules **102**, **104**, **106**, **108** may form a battery pack. In such examples, each battery module **102**, **104**, **106**, **108** may include battery cells. In some examples, some or all of the battery modules **102**, **104**, **106**, **108** may have a different number of cells. For example, the battery module **102** may have N cells and the battery module **104** may have M cells, where N and M are different integers greater than zero. Further, in some examples, some or all of the battery modules **102**, **104**, **106**, **108** may have different dimensions. For instance, the height of the battery module **102** may be different than the height of the battery module **104**.

[0053] For example, FIGS. **2-3** depict one example configuration of a battery pack **200** including the battery modules **102**, **104**, **106**, **108**. In the example of FIGS. **2-3**, the battery pack **200** may be referred to as a RESS battery pack, and the battery modules **102**, **104** are collectively shown as a battery module **202**.

[0054] In various embodiments, a cell configuration tool may be utilized to maximize energy of the battery pack **200** with multiple form factor cells. For example, and as shown in FIGS. **2-3**, the battery pack **200** includes three layers (or regions), with different sizes and heights. In such examples, the three layers with multiple heights are divided and packed with different battery cells to form the battery modules **106**, **108**, **202**. For example, the battery module **108** includes cells **208**, the battery module **106** includes cells **210**, and the battery module **202** includes cells **212**, **214**. More specifically, the battery module **102** of FIG. **1** may include the cells **212**, and the battery module **104** of FIG. **1** may include the cells **214**. In such examples, prismatic cells may be packed with hybrid orientations, such a mixture of left/right and fore/aft cells. If desired, a pixel based 2D tool may be used to achieve a maximum pack volumetric efficiency when forming the battery modules **106**, **108**, **202** for the battery pack **200**.

[0055] As shown in FIGS. **2-3**, the battery modules **106**, **108**, **202** have different dimensions. For example, the battery module **108** (e.g., a high domain) has a height of about 425 mm (in the y direction in FIG. **3**) and a width of about 600 mm (in the x direction in FIG. **3**), the battery module **106** (e.g., an intermediate domain) has a height of about 275 mm (in the y direction) and a width of about 300 mm (in the y direction), and the battery module **202** (e.g., a low domain) has a height of about 125 mm (in the y direction) and a width of about 2100 mm (in the x direction). While specific dimensions and/or characteristics are described for the battery modules **106**, **108**, **202** and cells therein, it should be appreciated that any one of the battery modules **106**, **108**, **202** and/or the cells therein may have another suitable height, width, capacity, etc. depending on, for example, load demand requirements, available space, cell characteristics, etc.

[0056] In various embodiments, the battery modules **106**, **108**, **202** may include a different number of cells in different configurations and having different characteristics, as shown in Tables 1 and 2 below. For example, the battery module **108** includes **136** cells each having a specific dimension and a specific capacity (e.g., 137 Ah). The battery module **106** includes 48 cells having different dimensions than the cells of the battery module **108** but the same capacity (e.g., 137 Ah). The battery module **202** (collectively, the battery module **102**, **104** of FIG. **1**) includes 620 cells each having a specific dimension and a specific capacity (e.g., 36.7 Ah).

TABLE-US-00001 TABLE 1 Cell Number Single Cell Capacity (Ah) Battery Module 108 136 137 Battery Module 106 48 137 Battery Module 202 620 36.7

[0057] In Table 2, a defined number of cells of the battery modules are coupled in parallel and then the parallel sets are coupled in series to achieve a desired voltage to meet load demands. For example, and as shown in Table 2, each set of two cells **208** in the battery module **108** are coupled in parallel to obtain 68 parallel pairs of cells. Then, the 68 parallel pairs of cells are coupled in series to obtain about 285.6 V (e.g., 4.2 volts for each parallel pair multiplied by 68 parallel pairs). The cells **210** of the battery module **106** are arranged similarly, but with 24 parallel pairs of cells to obtain about 100.8 V (e.g., 4.2 volts for each parallel pair multiplied by 24 parallel pairs). The cells **214** of the battery module **104** are broken into sets of seven cells coupled in parallel to obtain 44 parallel pairs. Then, the 44 parallel pairs of cells are coupled in series to obtain about 184.8 V (e.g., 4.2 volts for each parallel pair multiplied by 44 parallel pairs). The cells **212** of the battery module **102** are arranged similarly, but with 39 parallel pairs of eight cells to obtain about 163.8 V (e.g., 4.2 volts for each parallel pair multiplied by 39 parallel pairs). As shown, the battery modules **106**, **108** have the same capacity of about 274 Ah, the battery module **104** has a capacity of about 259.9 Ah, and the battery module **102** has a capacity of about 293.6 Ah.

TABLE-US-00002 TABLE 2 Number of Battery Maximum individual Module Number of Module cells in Capacity Parallel Voltage parallel (Ah) Pairs (V) Cells 208 2 274 68 285.6 Cells 210 2 274 24 100.8 Cells 214 (of 7 256.9 44 184.8 battery module 104) Cells 212 (of 8 293.6 39 163.8 battery module 102)

[0058] With continued reference to FIG. **1**, the battery modules **102**, **104**, **106**, **108** may have the same or different chemical compositions. For example, any one of the battery modules **102**, **104**, **106**, **108** (or cells therein) may have a lithium-nickel-cobalt-manganese oxide (NMC) composition, and another one of the battery modules **102**, **104**, **106**, **108** (or cells therein) may have a lithium ferrophosphate (LFP) composition.

[0059] For example, FIG. **4** depicts another example power system **400** similar to the power system **100** of FIG. **1**. For example, the power system **400** of FIG. **4** includes a DC-DC converter **412** having the power switches **114**, **116** coupled in parallel with the battery modules **102**, **104**, and the inductor **118** coupled between the power switches **114**, **116** and the battery modules **102**, **104**. In the example of FIG. **4**, the DC-DC converter **412** does not include the filter capacitors. The battery modules **102**, **104** are coupled to the component(s) **110**.

[0060] In FIG. **4**, the battery modules **102**, **104** include different chemical compositions. For example, the battery module **102** has a NMC composition while the battery module **104** has a LFP composition. While the battery modules **102**, **104** of FIG. **4** are described as having NMC and LFP compositions, it should be appreciated that the battery modules **102**, **104** may have any suitable chemical compositions.

[0061] In the example of FIG. **4**, the power switches **114**, **116** of the DC-DC converter **412** can be controlled to balance the SOC of the battery module **102** and the SOC of the battery module **104**, as explained herein. This may be particularly useful given the aging behavior differences for NMC and LFP cells. For example, LFP cells of the battery module **104** typically age slower than NMC cells of the battery module **102**. In such examples, the battery module **104** may endure more charging/discharging cycles before its state of health (SOH) deteriorates than the battery module **106**.

[0062] FIG. **5** depicts another example power system **500** similar to the power system **100** of FIG. **1** but including a control module **550** coupled to the DC-DC converter **112**. Specifically, the power system **500** includes the DC-DC converter **112** of FIG. **1**, the battery modules **102**, **104**, **106**, **108** of FIG. **1**, the component(s) **110** of FIG. **1**, the control module **550**, a current sensor **552**, and voltage sensors **556**, **560**. The DC-DC converter **112** includes the power switches **114**, **116**, the inductor **118**, and the optional capacitors **120**, **122** of FIG. **1**. Additionally, the battery modules **102**, **104** have different capacities, as explained above. For instance, the battery module **102** may have a higher capacity than the battery module **104**.

[0063] In the example of FIG. **5**, the control module **550** senses parameters associated with the battery modules **102**, **104** and the inductor **118**. For example, the control module **550** senses voltages of the battery modules **102**, **104** via the voltage sensors **556**, **560**, respectively, and a current flowing through the inductor **118** via the current sensor **552**. In such examples, the voltage sensors **556**, **560** may transmit voltage feedback signals **558**, **562** indicative of the sensed voltages to the control module **550**, and the current sensor **552** may transmit a current feedback signal **554** indicative of the sensed inductor current to the control module **550**.

[0064] Then, the control module **550** may control the power switches **114**, **116** based on the sensed battery voltage and inductor current to balance the SOC of the battery module **102** and the SOC of the battery module **104**. For example, the control module **550** may calculate the SOC of the battery module **102** based on the voltage feedback signal **558** and the SOC of the battery module **104** based on the voltage feedback signal **562**. In such examples, the control module **550** may implement conventional methods for calculating the SOCs of the battery modules **102**, **104** based on the sensed battery voltages. The control module **550** may then generate control signals (e.g., pulse width modulated (PWM) control signals) **564**, **566** for controlling the power switches **114**, **116**. For example, if the SOCs of the battery modules **102**, **104** are unbalanced (e.g., based on a comparison of the calculated SOCs), the control module **550** generates the control signals **564**, **566** based on the sensed inductor current to control the amount of current flowing through the inductor **118** to balance the SOCs of the battery modules **102**, **104**.

[0065] For example, the battery modules **102**, **104**, **106**, **108** and the control module **550** may operate in a discharging mode or a charging mode. The discharging mode represents instances when the battery modules **102**, **104**, **106**, **108** provide power to the load, whereas the charging mode represents instances when the battery modules **102**, **104**, **106**, **108** receive power. In some examples, the control module **550** may transition from one mode to the other mode based on current flow. For instance, the control module **550** may detect or sense current flowing towards the battery modules **102**, **104**, **106**, **108** from the component(s) **110** (in this case the charging source(s)) and operate in the charging mode. In other examples, the control module **550** may detect or sense current flowing towards the component(s) **110** (in this case the load(s)) from the battery modules **102**, **104**, **106**, **108** and operate in the discharging mode.

[0066] When operating in the discharging mode, the control module **550** may control a duty cycle of the control signal **564** for the power switch **114** to cause current to discharge from the battery module **102** (e.g., the higher capacity battery module) to the battery module **104** (e.g., the lower capacity battery module) via the inductor **118**. During this time, the power switch **116** is turned off (e.g., open). With this configuration, the battery module **102** provides additional current to charge the battery module **104**, the amount of which is controllable based on the duty cycle. As a result, the battery module **104** provides less current to the load as compared to the battery modules **102**, **106**, **108**, thereby causing the SOC of the battery module **102** to decrease at a faster rate than the SOC of the battery module **104**.

[0067] For example, FIGS. **6-7** each depict the power system **100** with the power switches **114**, **116**

and the battery modules **102**, **104**, **106**, **108**. In FIGS. **6-7**, the power system **100** is in a discharging mode. During this time, current (represented by the dashed arrowed lines) flows from the battery modules **102**, **104**, **106**, **108** to the component(s) **110** (e.g., a load in this case). In the example of FIG. **6**, the power switch **114** is controlled and the power switch **116** is turned off. In the example of FIG. **7**, the power switch **114** is turned off and the power switch **116** is controlled. FIG. **8** depicts current **802** of the battery module **102**, current **804** of the battery module **104**, current **806** of the battery modules **106**, **108**, inductor current **808**, and control signals **810**, **812** for the power switches **114**, **116**, respectively, of FIGS. **6-7**.
[0068] If, however, the control module **550** is operating in the charging mode, the control module **550** may control a duty cycle of the control signal **566** for the power switch **116** to cause current to discharge from the battery module **104** (e.g., the lower capacity battery module) to the battery module **102** (e.g., the higher capacity battery module) via the inductor **118**. During this time, the power switch **114** is turned off (e.g., open). In such examples, the battery module **102** receives additional current from the battery module **104** to charge the battery module **102**, the amount of which is controllable based on the duty cycle. As a result, the battery module **104** receives less charging current as compared to the battery modules **102**, **106**, **108**. In turn, this causes the SOC of the battery module **102** to increase at a faster rate than the SOC of the battery module **104**.
[0069] For example, FIGS. **9-10** each depict the power system **100** with the power switches **114**, **116** and the battery modules **102**, **104**, **106**, **108**. In FIGS. **9-10**, the power system **100** is in a charging mode. During this time, current (represented by the dashed arrowed lines) flows from the component(s) **110** (e.g., a charger in this case) to the battery modules **102**, **104**, **106**, **108**. In the example of FIG. **9**, the power switch **114** is controlled and the power switch **116** is turned off. In the example of FIG. **10**, the power switch **114** is turned off and the power switch **116** is controlled. FIG. **11** depicts current **1102** of the battery module **102**, current **1104** of the battery module **104**, current **1106** of the battery modules **106**, **108**, inductor current **1108**, and control signals **1110**, **1112** for the power switches **114**, **116**, respectively, of FIGS. **9-10**.
[0070] FIG. **12** depicts an example control circuit **1200** for the control module **550** of FIG. **5** for controlling the DC-DC converter **112** to balance the SOCs of the battery modules **102**, **104**. As shown, the control circuit **1200** of FIG. **12** includes SOC generators **1202**, **1204**, a voltage loop controller **1206**, a target current generator **1208**, a current loop controller **1210**, a PWM generator **1212**, and a filter **1214**. Although the control circuit **1200** of FIG. **12** is described and shown as including specific components and functions, it should be appreciated that other suitable implementations may be employed to balance the SOCs of the battery modules **102**, **104**.
[0071] In the example of FIG. **12**, the SOC generators **1202**, **1204** calculate the SOCs of the battery modules **102**, **104**. This may be done based on the received voltage feedback signals **558**, **562**, as explained herein. Then, a voltage comparator **1216** compares the calculated SOCs of the battery modules **102**, **104**, and outputs a SOC error signal to the voltage loop controller **1206** based on the comparison. The voltage loop controller **1206** then generates and outputs a voltage signal based on the SOC error signal.
[0072] Then, the target current generator **1208** generates a commanded or target inductor current. More specifically, the target current generator **1208** receives the voltage signal from the voltage loop controller **1206** and generates a signal indicative of the target inductor current. A current comparator **1218** then compares the target inductor current and the sensed inductor current (obtained via the current feedback signal **554**), and outputs a current error signal to the current loop controller **1210** based on the comparison. In various embodiments, the current feedback signal **554** may pass through the filter **1214** (e.g., a low-pass filter, etc.) before reaching the current comparator **1218**, as shown in FIG. **6**.
[0073] Next, the current loop controller **1210** generates and outputs a current signal based on the current error signal. In various embodiments, the current loop controller **1210** may be a proportional and integral (PI) controller or another suitable controller. The PWM generator **1212**

then generates the control signals **564**, **566** for the power switches **114**, **116** based on the current signal from the current loop controller **1210**.

[0074] FIGS. **13-14** depict graphs representing various current characteristics of the power system **100** of FIG. **1** over time during discharging and charging modes. Specifically, graphs **1302**, **1306**, **1310**, **1314**, **1318** of FIG. **13** represent current values during a discharging mode, and graphs **1402**, **1406**, **1410**, **1414**, **1418** of FIG. **14** represent current values during a charging mode. In FIGS. **13-14**, the graphs **1302**, **1402** show the combined current **1304**, **1404** of the battery modules **106**, **108**, the graphs **1306**, **1406** show the current **1308**, **1408** of the battery module **104**, the graphs **1310**, **1410** show the current **1312**, **1412** of the battery module **102**, the graphs **1314**, **1414** show the load current **1316**, **1416**, and the graphs **1318**, **1418** show the inductor current **1320**, **1420**. As shown in FIGS. **13-14**, the inductor current **1320**, **1420** is adjusted (e.g., controlled based on current of the power switches **114**, **116**), thereby causing the current **1308**, **1408** of the battery module **104** and the current **1312**, **1412** of the battery module **102** to change.

[0075] In various embodiments, any one of the power systems disclosed herein may be employable in any suitable vehicle, such as an EV (e.g., a pure electric vehicle, a plug-in hybrid electric vehicle, etc.). In other examples, the power systems disclosed herein may be implemented in other suitable non-vehicle applications including rechargeable battery modules having different capacities and/or chemical compositions.

[0076] As one example, FIG. **15** depicts an EV **1500** including the control module **550** of FIG. **5**, the DC-DC converter **112** of FIG. **1**, and battery modules **1502** (e.g., representing the battery modules **102**, **104** of FIG. **1** or **4**). A load and a charging source may be coupled to the battery modules **1502**, as explained herein.

[0077] FIG. **16** illustrates an example control process **1600** employable by the power system **500** of FIG. **5** for balancing SOCs of the battery modules **102**, **104**. Although the example control process **1600** is described in relation to the power system **500** of FIG. **5** including the control module **550**, the control process **1600** may be employable by another suitable power system and/or control module. Additionally, the power systems and the control modules herein, such as the power system **500** and the control module **550**, should not be understood to be limited to the exemplary control process **1600**.

[0078] As shown in FIG. **16**, the process **1600** may begin at **1602** where the control module **550** senses parameters associated with the battery modules **102**, **104**. For example, and as explained above, the control module **550** may sense voltages of the battery modules **102**, **104** via the voltage sensors **556**, **560**, respectively. Control then proceeds to **1604**.

[0079] At **1604**, the control module **550** calculates a SOC of each battery module **102**, **104**. For instance, the control module **550** may determine the SOC of each battery module **102**, **104** based on the corresponding sensed battery module voltage and a known discharge curve for that battery module. Control then proceeds to **1606**.

[0080] At **1606**, the control module **550** determines whether the SOCs of the battery modules **102**, **104** are balanced. For example, the control module **550** may compare the SOCs of the battery modules **102**, **104** to determine if the SOCs are substantially the same (e.g., the same or within a nominal percent, such as plus/minus 0.5%, 1%, 2%, 3%, etc.). In other examples, the control module **550** may compare one or both SOCs of the battery modules **102**, **104** to a target SOC to determine if the SOCs are substantially the same. In some examples, the target SOC may be set to a defined percentage achievable by both battery modules **102**, **104** at the same time, set to one of the calculated SOCs of the battery modules **102**, **104**, etc. If the control module **550** determines that the SOCs of the battery modules **102**, **104** are balanced at **1006**, control may end as shown in FIG. **10** or return to another suitable step, such as **1002** if desired. If, however, the control module **550** determines that the SOCs of the battery modules **102**, **104** are not balanced (e.g., the SOCs are different, one or both SOCs differs from the target SOC, etc.), control proceeds to **1608**.

[0081] At **1608**, the control module **550** generates and transmits control signals based on the sensed parameters for controlling the DC-DC converter **112**. For example, and as explained above, the control module **550** may generate the control signals (e.g., PWM control signals) **564**, **566** for controlling the power switches **114**, **116** based on the sensed battery module voltages and/or one or more converter parameters, such as a sensed current flowing through the inductor **118**. In such examples, the control module **550** may control one of the power switches **114**, **116** to modulate and the other power switch **114**, **116** to turn off depending on whether the power system **500** is operating in a discharging mode or a charging mode, as explained herein. In doing, one of the battery modules **102**, **104** may discharge current to or receive current from the other battery module **102**, **104** to balance the SOCs of the battery modules **102**, **104**. Control may end as shown in FIG. **16** or return to another suitable step, such as **1602** if desired.

[0082] The foregoing description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. The broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. It should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure. Further, although each of the embodiments is described above as having certain features, any one or more of those features described with respect to any embodiment of the disclosure can be implemented in and/or combined with features of any of the other embodiments, even if that combination is not explicitly described. In other words, the described embodiments are not mutually exclusive, and permutations of one or more embodiments with one another remain within the scope of this disclosure.

[0083] Spatial and functional relationships between elements (for example, between modules, circuit elements, semiconductor layers, etc.) are described using various terms, including “connected,” “engaged,” “coupled,” “adjacent,” “next to,” “on top of,” “above,” “below,” and “disposed.” Unless explicitly described as being “direct,” when a relationship between first and second elements is described in the above disclosure, that relationship can be a direct relationship where no other intervening elements are present between the first and second elements, but can also be an indirect relationship where one or more intervening elements are present (either spatially or functionally) between the first and second elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A OR B OR C), using a non-exclusive logical OR, and should not be construed to mean “at least one of A, at least one of B, and at least one of C.”

[0084] In the figures, the direction of an arrow, as indicated by the arrowhead, generally demonstrates the flow of information (such as data or instructions) that is of interest to the illustration. For example, when element A and element B exchange a variety of information but information transmitted from element A to element B is relevant to the illustration, the arrow may point from element A to element B. This unidirectional arrow does not imply that no other information is transmitted from element B to element A. Further, for information sent from element A to element B, element B may send requests for, or receipt acknowledgements of, the information to element A.

[0085] In this application, including the definitions below, the term “module” or the term “controller” may be replaced with the term “circuit.” The term “module” may refer to, be part of, or include: an Application Specific Integrated Circuit (ASIC); a digital, analog, or mixed analog/digital discrete circuit; a digital, analog, or mixed analog/digital integrated circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor circuit (shared, dedicated, or group) that executes code; a memory circuit (shared, dedicated, or group) that stores code executed by the processor circuit; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip.

[0086] The module may include one or more interface circuits. In some examples, the interface circuits may include wired or wireless interfaces that are connected to a local area network (LAN), the Internet, a wide area network (WAN), or combinations thereof. The functionality of any given module of the present disclosure may be distributed among multiple modules that are connected via interface circuits. For example, multiple modules may allow load balancing. In a further example, a server (also known as remote, or cloud) module may accomplish some functionality on behalf of a client module.

[0087] The term code, as used above, may include software, firmware, and/or microcode, and may refer to programs, routines, functions, classes, data structures, and/or objects. The term shared processor circuit encompasses a single processor circuit that executes some or all code from multiple modules. The term group processor circuit encompasses a processor circuit that, in combination with additional processor circuits, executes some or all code from one or more modules. References to multiple processor circuits encompass multiple processor circuits on discrete dies, multiple processor circuits on a single die, multiple cores of a single processor circuit, multiple threads of a single processor circuit, or a combination of the above. The term shared memory circuit encompasses a single memory circuit that stores some or all code from multiple modules. The term group memory circuit encompasses a memory circuit that, in combination with additional memories, stores some or all code from one or more modules.

[0088] The term memory circuit is a subset of the term computer-readable medium. The term computer-readable medium, as used herein, does not encompass transitory electrical or electromagnetic signals propagating through a medium (such as on a carrier wave); the term computer-readable medium may therefore be considered tangible and non-transitory. Non-limiting examples of a non-transitory, tangible computer-readable medium are nonvolatile memory circuits (such as a flash memory circuit, an erasable programmable read-only memory circuit, or a mask read-only memory circuit), volatile memory circuits (such as a static random access memory circuit or a dynamic random access memory circuit), magnetic storage media (such as an analog or digital magnetic tape or a hard disk drive), and optical storage media (such as a CD, a DVD, or a Blu-ray Disc).

[0089] The apparatuses and methods described in this application may be partially or fully implemented by a special purpose computer created by configuring a general purpose computer to execute one or more particular functions embodied in computer programs. The functional blocks, flowchart components, and other elements described above serve as software specifications, which can be translated into the computer programs by the routine work of a skilled technician or programmer.

[0090] The computer programs include processor-executable instructions that are stored on at least one non-transitory, tangible computer-readable medium. The computer programs may also include or rely on stored data. The computer programs may encompass a basic input/output system (BIOS) that interacts with hardware of the special purpose computer, device drivers that interact with particular devices of the special purpose computer, one or more operating systems, user applications, background services, background applications, etc.

[0091] The computer programs may include: (i) descriptive text to be parsed, such as HTML (hypertext markup language), XML (extensible markup language), or JSON (JavaScript Object Notation) (ii) assembly code, (iii) object code generated from source code by a compiler, (iv) source code for execution by an interpreter, (v) source code for compilation and execution by a just-in-time compiler, etc. As examples only, source code may be written using syntax from languages including C, C++, C #, Objective-C, Swift, Haskell, Go, SQL, R, Lisp, Java®, Fortran, Perl, Pascal, Curl, OCaml, JavaScript®, HTML5 (Hypertext Markup Language 5th revision), Ada, ASP (Active Server Pages), PHP (PHP: Hypertext Preprocessor), Scala, Eiffel, Smalltalk, Erlang, Ruby, Flash®, Visual Basic®, Lua, MATLAB, SIMULINK, and Python®.

Claims

1. A system for a vehicle, the system comprising: a first battery module having a first capacity; a second battery module having a second capacity different than the first capacity; a DC-DC converter coupled to the first battery module and the second battery module; and a control module coupled to the DC-DC converter, the control module configured to sense a first parameter associated with the first battery module and a second parameter associated with the second battery module, and control the DC-DC converter based on the first parameter and the second parameter to balance a state of charge of the first battery module and a state of charge of the second battery module.
2. The system of claim 1, wherein the DC-DC converter includes a first power switch coupled in parallel with the first battery module, a second power switch coupled in parallel with the second battery module, and an inductor coupled between the first and second power switches and the first and second battery modules.
3. The system of claim 2, wherein the control module is configured to: sense a current flowing through the inductor; and control the DC-DC converter based on the sensed current, the first parameter and the second parameter to balance the state of charge of the first battery module and the state of charge of the second battery module.
4. The system of claim 2, wherein the control module is configured to control a current flowing through the inductor to balance the state of charge of the first battery module and the state of charge of the second battery module.
5. The system of claim 4, wherein: the first capacity of the first battery module is greater than the second capacity of the second battery module; and the control module is configured to control the first power switch with a pulse width modulated control signal to discharge current from the first battery module to the second battery module via the inductor, when the control module is in a discharging mode in which the first battery module and the second battery module provide power a load.
6. The system of claim 4, wherein: the first capacity of the first battery module is greater than the second capacity of the second battery module; and the control module is configured to control the second power switch with a pulse width modulated control signal to discharge current from the second battery module to the first battery module via the inductor, when the control module is in a charging mode in which the first battery module and the second battery module are receiving power.
7. The system of claim 2, wherein the DC-DC converter includes a first capacitor coupled in parallel with the first power switch, and a second capacitor coupled in parallel with the second power switch.
8. The system of claim 1, wherein the first parameter is a voltage of the first battery module, and the second parameter is a voltage of the second battery module.
9. The system of claim 1, wherein: the first battery module includes a plurality of cells; the second battery module includes a plurality of cells; and a chemical composition of at least one cell of the first battery module is different than a chemical composition of at least one cell of the second battery module.
10. The system of claim 9, wherein the at least one cell of the first battery module is a lithium-nickel-cobalt-manganese oxide (NMC) cell, and the at least one cell of the second battery module is a lithium ferrophosphate (LFP) cell.
11. The system of claim 1, wherein: the first battery module includes N cells; the second battery module includes M cells; and N and M are integers greater than zero, and N is different than M.
12. The system of claim 1, wherein: the first battery module includes a plurality of cells; the second battery module includes a plurality of cells; and at least one dimension of the first battery module is different than a corresponding dimension of the second battery module.
13. A vehicle comprising the system of claim 1 and at least one load coupled to the first battery

module and the second battery module.

14. A method of controlling a DC-DC converter in a vehicle to balance a state of charge of a first battery module and a state of charge of a second battery module, the DC-DC converter including a first power switch coupled in parallel with the first battery module, a second power switch coupled in parallel with the second battery module, and an inductor coupled between the first and second power switches and the first and second battery modules, the first battery module having a first capacity, the second battery module having a second capacity different than the first capacity, the method comprising: sensing at least one first parameter associated with the first battery module and at least one second parameter associated with the second battery module; and controlling the first power switch or the second power switch based on the first parameter and the second parameter to balance the state of charge of the first battery module and the state of charge of the second battery module.

15. The method of claim 14, wherein: the first capacity of the first battery module is greater than the second capacity of the second battery module; and controlling the first power switch or the second power switch includes controlling the first power switch with a pulse width modulated control signal to discharge current from the first battery module to the second battery module via the inductor, when the first battery module and the second battery module are providing power a load.

16. The method of claim 14, wherein: the first capacity of the first battery module is greater than the second capacity of the second battery module; and controlling the first power switch or the second power switch includes controlling the second power switch with a pulse width modulated control signal to discharge current from the second battery module to the first battery module via the inductor, when the first battery module and the second battery module are receiving power.

17. The method of claim 14, wherein: the first battery module includes a plurality of cells; the second battery module includes a plurality of cells; and a chemical composition of at least one cell of the first battery module is different than a chemical composition of at least one cell of the second battery module.

18. The method of claim 17, wherein the at least one cell of the first battery module is a lithium-nickel-cobalt-manganese oxide (NMC) cell, and the at least one cell of the second battery module is a lithium ferrophosphate (LFP) cell.

19. The method of claim 14, wherein: the first battery module includes N cells; the second battery module includes M cells; and N and M are integers greater than zero, and N is different than M.

20. The method of claim 14, wherein: the first battery module includes a plurality of cells; the second battery module includes a plurality of cells; and at least one dimension of the first battery module is different than a corresponding dimension of the second battery module.