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Inventor(s)	Hao; Lei et al.

Balancing of battery packs via DC-to-DC converters and motor inverter circuits

Abstract

A charging system includes: a charge port that receives shore power; a DC-to-DC converter or a motor inverter circuit; switches that connect the charge port and the DC-to-DC converter or the motor inverter circuit to battery packs; and a control module. The control module: determines open circuit voltages or states of charges of the battery packs; based on the open circuit voltages or the states of charges of the battery packs, determines whether to connect at least one of the battery packs to the charge port, the DC-to-DC converter, and the motor inverter circuit; and based on the determination of whether to connect at least one of the battery packs, control states of the switches to charge the at least one of the battery packs by selectively connecting the at least one of the battery packs to (a) the charge port, or (b) the DC-to-DC converter or motor inverter circuit.

Inventors: **Hao; Lei (Troy, MI), Wang; Yue-Yun (Troy, MI), Zhu; Yongjie (Troy, MI)**

Applicant: **GM GLOBAL TECHNOLOGY OPERATIONS LLC** (Detroit, MI)

Family ID: **1000008748761**

Assignee: **GM GLOBAL TECHNOLOGY OPERATIONS LLC (Detroit, MI)**

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Background/Summary

INTRODUCTION

(1) 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.
(2) The present disclosure relates to power sources for electric vehicles.
(3) Electric vehicles include one or more power sources for supplying electrical energy to one or more electric motors. The electric motors are utilized for propulsion purposes and can also be used to reduce speed of the vehicles and recharge, for example, cells of the power sources. As an example, the electric motors may be operated as generators during regenerative braking operation to decelerate the vehicles and/or recharge the power sources.
SUMMARY
(4) A charging system is disclosed and includes: one or more charge ports configured to receive shore power; at least one of a direct current (DC)-to-DC converter or a motor inverter circuit; switches configured to connect the one or more charge ports and the at least one of the DC-to-DC converter or the motor inverter circuit to battery packs; and a control module configured to (i) determine at least one of open circuit voltages or states of charges of the battery packs, (ii) based on the at least one of the open circuit voltages or the states of charges of the battery packs,

determine whether to connect at least one of the battery packs to the one or more charge ports, the DC-to-DC converter, and the motor inverter circuit, and (iii) based on the determination of whether to connect the at least one of the battery packs, control states of the switches to charge the at least one of the battery packs by selectively connecting the at least one of the battery packs to at least one of (a) the one or more charge ports, or (b) the at least one of the DC-to-DC converter or the motor inverter circuit.

(5) In other features, the charging system further includes sensors configured to detect the open circuit voltages of the battery packs.

(6) In other features, the switches are configured to connect the one or more charge ports to the battery packs. The control module is configured to, based on the at least one of the open circuit voltages or the states of charges of the battery packs, control the states of the switches to charge at least one of the battery packs by selectively connecting the at least one of the battery packs to the one or more charge ports.

(7) In other features, the charging system includes the DC-to-DC converter. The switches are configured to connect the one or more charge ports and the DC-to-DC converter to the battery packs. The control module is configured, based on the at least one of the open circuit voltages or the states of charges of the battery packs, to control the states of the switches to charge the at least one of the battery packs by selectively connecting the at least one of the battery packs to the DC-to-DC converter.

(8) In other features, the control module is configured to control the states of the switches to charge a selected one or more of the battery packs via the one or more charge ports and the DC-to-DC converter.

(9) In other features, the switches are configured to connect the motor inverter circuit to the battery packs. The control module is configured to, based on the at least one of the open circuit voltages or the states of charges of the battery packs, control the states of the switches to charge at least one of the battery packs by selectively connecting the at least one of the battery packs to the motor inverter circuit.

(10) In other features, the control module is configured to control the states of the switches to charge a selected one or more of the battery packs via the one or more charge ports and the motor inverter circuit.

(11) In other features, the motor inverter circuit includes: an inverter; and a motor configured to receive power from the battery packs or the one or more charge ports via the inverter.

(12) In other features, the control module is configured to: control the states of the switches to connect (i) the battery packs in series and to terminals of the one or more charge ports; and change the states of the switches to connect the one or more charge ports to an input of the DC-to-DC converter, and (ii) an output of the DC-to-DC converter to one or more of the battery packs.

(13) In other features, the battery packs include a first battery pack and a second battery pack. The control module is configured to control the states of the switches to (i) connect the first battery pack to an input of the DC-to-DC converter, and (ii) an output of the DC-to-DC converter to the second battery pack to perform charge balancing via the DC-to-DC converter.

(14) In other features, the one or more charge ports include charge ports. Each of the charge ports are configured to be connected to each of the battery packs based on states of the switches. The control module is configured to independently charge each of the battery packs with one or more of the charge ports.

(15) In other features, the control module is configured to: control the states of the switches to series charge the battery packs; and subsequent to series charging the battery packs, cease charging of a first one of the battery packs and continue charging of a second one of the battery packs until an open circuit voltage of the second one of the battery packs is within a predetermined range of an open circuit voltage of the first one of the battery packs.

(16) In other features, the charging of the second one of the battery packs is performed via the at

least one of the DC-to-DC converter or the motor inverter circuit.

(17) In other features, subsequent to charging the second one of the battery packs, the control module is configured to control states of the switches to connect the battery packs in parallel.

(18) In other features, the control module is configured to calculate an open circuit voltage of one of the battery packs based on open circuit voltages of modules of the one of the battery packs.

(19) In other features, the control module is configured to subsequent to series charging the battery packs, determine a first one of the battery packs has a lower capacity and a higher open circuit voltage than a second one of the battery packs, and charge the second one of the battery packs via the first one of the battery packs.

(20) In other features, the charging of the second one of the battery packs is performed via the at least one of the DC-to-DC converter or the motor inverter circuit.

(21) In other features, the control module is configured, subsequent to the charging of at least one of the battery packs, to at least one of: control the states of the switches to (i) connect the battery packs in parallel and to an input of the DC-to-DC converter, and (ii) connect an output of the DC-to-DC converter to a load; or control the states of the switches to connect the battery packs in parallel and to an input of the motor inverter circuit to drive a motor of the motor inverter circuit.

(22) In other features, a charging system is disclosed and includes: one or more charge ports configured to receive shore power; a direct current (DC)-to-DC converter; switches configured to connect the one or more charge ports and the DC-to-DC converter to battery packs; and a control module configured to (i) control states of the switches to series charge the battery packs, (ii) subsequent to series charging the battery packs, determine at least one of open circuit voltages or states of charges of the battery packs, and (iii) based on the at least one of the open circuit voltages or the states of charges of the battery packs, charge one of the battery packs by selectively connecting the one of the battery packs to the DC-to-DC converter and (a) another one of the battery packs, or (b) the one or more charge ports.

(23) In other features, a charging system is disclosed and includes: one or more charge ports configured to receive shore power; a motor inverter circuit; switches configured to connect the one or more charge ports and the motor inverter circuit to battery packs; and a control module configured to (i) control states of the switches to series charge the battery packs, (ii) subsequent to series charging the battery packs, determine at least one of open circuit voltages or states of charges of the battery packs, and (iii) based on the at least one of the open circuit voltages or the states of charges of the battery packs, charge one of the battery packs by selectively connecting the one of the battery packs to the motor inverter circuit and (a) another one of the battery packs, or (b) the one or more charge ports.

(24) 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

(1) The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

(2) FIG. **1**A is an example plot of in-rush current versus time for battery packs having a 5% state of charge (SOC) imbalance;

(3) FIG. **1**B is an example plot of in-rush current versus time for battery packs having 1% SOC imbalance;

(4) FIG. **2** is a functional block diagram of an example of a charging system including a vehicle with a charging circuit in accordance with the present disclosure;

(5) FIG. **3** is a functional block diagram of an example of a propulsion system including a power source with a charging circuit in accordance with the present disclosure;

(6) FIG. **4** is a schematic functional block diagram of a charging circuit configured for charge balancing via charge port and a DC-to-DC converter in accordance with the present disclosure;

(7) FIG. **5** is a schematic functional block diagram of a charging circuit configured for charge balancing between battery packs via a DC-to-DC converter in accordance with the present disclosure;

(8) FIG. **6** is a schematic functional block diagram of a charging circuit configured for independent charging and/or charge balancing of battery packs via respective charge ports in accordance with the present disclosure;

(9) FIG. **7** is a schematic functional block diagram of a charging circuit configured for independent charging and/or charge balancing of battery packs via respective charge ports and a motor inverter circuit in accordance with the present disclosure;

(10) FIG. **8** is an example plot of open circuit voltage (VOC) versus state of charge (SOC) in accordance with the present disclosure; and

(11) FIG. **9** illustrates an example charging method implemented by a control module or battery management module in accordance with the present disclosure.

(12) In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DETAILED DESCRIPTION

(13) Series and parallel battery configurations are implemented in electric vehicles. Battery packs, which may include battery modules with hundreds of battery cells, can become imbalanced. This imbalance may occur after charging of the battery packs is completed. As an example, two battery packs may be connected in series to receive a high voltage (e.g., 800 Volts (V)) and, when series charging is completed, may be connected in parallel to supply a lower voltage (e.g., 400 V) to direct current (DC) loads. As another example, two battery packs may be disconnected and independently charged, when charging is completed, two pack may be connected in parallel to supply a voltage to DC loads. After charging of the two battery packs, the SOCs of the batteries may be imbalanced. For example, one battery pack may have 5% more SOC than the other battery pack. The battery pack with the higher SOC can be the battery pack with a smaller capacity due to aging. This can cause an in-rush of current from the battery pack with the higher SOC to the battery pack with the lower SOC. This can reduce life of the battery pack with the lower capacity and can also reduce life of contactors (or switches) implemented in a charging circuit and reduce available power.

(14) FIG. **1**A shows an example plot of in-rush current versus time for battery packs A and B having a 5% SOC) imbalance between them. Battery pack A may be at 95% SOC and battery pack B may be at 90% SOC. When connected in parallel, there is an in-rush of current from battery pack A to battery pack B. Current flowing through battery pack A is in an opposite direction than current flowing through battery back B. The in-rush of current is shown by the initial spikes in magnitudes of current in the curves A**1**, B**1**. FIG. **1**B shows another example plot of in-rush current versus time for battery packs A, B having a 1% SOC imbalance between them. The y-axis scale of FIG. **1**B may be the same as the y-axis scale of FIG. **1**A. As shown by curves A**2**, B**2**, the amount of in-rush current is substantially less, when the amount of imbalance is less.

(15) The examples set forth herein include charging circuits for balancing SOCs across multiple battery packs. The examples include charging circuits and methods to charge battery packs and balance VOCs and SOCs of the battery packs using charge ports, DC-to-DC converters, motor inverter circuits, and switch circuits. The balancing may occur after high-voltage (e.g., 800V) port charging via a charging station (referred to as shore power). As a result, the in-rush current is greatly reduced while two packs are connected in parallel.

(16) In one embodiment, after charging via a charging station is completed, in which case the

battery packs of a power source may be connected in series, a drive system is used to charge a battery pack having a low VOC and/or SOC as compared to another battery pack. This charging balances the VOC and SOC of the battery packs prior to the battery packs being connected in parallel. The balancing of VOCs refers to reducing a difference between the VOCs of the battery packs. The balancing of the SOCs refers to reducing a difference between the SOCs of the battery packs. Multiple charging configurations are disclosed that include a DC-to-DC converter or a drive system for battery pack charging. The drive system includes a motor and an inverter, which are collectively referred to herein as a motor inverter circuit.

(17) In some embodiments, one or more charging ports are used to charge battery packs. One or more ports may be used to selectively charge a "weak" battery pack (or battery pack) having a lower VOC and/or lower SOC than another (or "strong") battery pack. The strong battery pack may be used to charge the weak battery pack.

(18) The VOCs and SOCs of battery packs may be monitored by a vehicle integration control module (herein after referred to as the vehicle control module) and/or a battery management module (BMM). The BMM may be a distributed wireless BMM (DWBMM), which may be implemented in a distributed wireless battery management system (DWBMS). In one embodiment, when the SOCs are monitored by the DWBMM, the DWBMM calculates the VOCs based on measured open circuit voltages (VOCMs) of battery modules within the battery packs, as further described below. In one embodiment, after a battery pack has aged and is now a weak battery pack, series charging of the battery packs is controlled based on the weak battery pack, as further described below. This is done such that the VOCs and SOCs are able to be balanced.

(19) FIG. **2** shows a charging system **200** including a vehicle **202** with a charging circuit **203**. The charging circuit **203** may be implemented as shown, for example, in FIGS. **3-7** and/or as described below. Although different embodiments are shown in FIGS. **3-7**, features of multiple embodiments may be combined. For example, one or more features of the embodiments of FIGS. **4-6** may be combined with one or more features of FIG. **7**. For example, charging and/or charge balancing may be provided via a DC-to-DC converter and/or a motor inverter circuit. The DC-to-DC circuits disclosed herein may be used for charging, charge balancing and/or for supplying power to one or more DC loads within the vehicle **202**, such as lights, displays, controllers, motors, fans, etc.

(20) The charging system **200** further includes a charging station **204** and a central monitoring station **206**. The vehicle **202** includes a propulsion system **208** having a power source **210** (hereinafter power source **210**) including the charging circuit **203**. The power source **210** may be dynamically adjustable to receive different maximum output voltages, current levels and/or power levels from different types of charging stations. In an embodiment, the power source **210** is configured to receive voltages within a particular voltage range.

(21) The propulsion system **208** further includes a telematics module **220**, vehicle control modules **222**, a memory **224**, motors **226**, **228** and a charging connector **230**. The telematics module **220** may include transceivers and communicate with the charging station **204**, the central monitoring station **206** and/or other infrastructure device. This communication may occur via a distributed communications system **232**. The telematics module **220** may communicate with infrastructure devices according to Wi-Fi, Bluetooth and/or wireless local area network, wide area network, and/or other communication protocols. The vehicle control modules **222** may include a body control module, a propulsion control module, a battery management module, etc. Although two motors are shown, any number of motors may be included. The motors **226**, **228** may be controlled by one or more of the vehicle control modules.

(22) The power source **210** may include any number of cells, battery packs, and/or power modules, which may be dynamically connected in various series and/or parallel arrangements to be compatible with different types of charging stations. The battery packs and/or modules within the battery packs may each include the same number of cells connected in a same arrangement, such that each battery pack has a same output voltage rating and output current rating. The cells, battery

packs, and/or power modules may also be dynamically connected in various series and/or parallel arrangements to accommodate different speed, acceleration and torque requests and/or operating modes. The power source **210** may be configured for: various voltage levels, such as maximum output voltages of 400V, 800V, and 1600V and/or nominal output voltages of 375V, 750V, and 1500V; and various power levels, such as maximum output power levels of 150 kW, 350 kW and 900 kW. The power source **210** may also be configured to command different maximum charging current levels, if needed, such as 200 A, 400 A, 500 A and 600 A depending on the state of charge and charge rate of the power source **210**.

(23) The power source **210** may be dynamically configurable to connect to different charging stations and to be charged at maximum voltage levels of the different charging stations or configured for particular type of charging station having a particular maximum voltage range. The power source **210** may include nominal low voltage energy storage devices (or battery packs), which are configurable for high voltage and high-power direct current (DC) charging.

(24) The propulsion system **208** may be configured to communicate with the charging stations, remote devices, and/or other infrastructure devices to determine capabilities of the charging stations and then dynamically be configured to be charged at maximum voltage levels of the charging stations. The propulsion system **208** may perform switch sequencing for transitioning switches to appropriate states to match the battery voltage of the vehicle to a maximum voltage of the currently connected charging station. As a result, the propulsion system **208** may be forward compatible for charging stations with maximum charging voltages higher than the native voltage of the vehicle (e.g., voltages greater than 800V for an 800V vehicle electric system) and backwards compatible for charging stations with maximum charging voltages lower than the native voltage of the vehicle (e.g., less than or equal to 800V for an 800V vehicle electric system).

(25) The charging station **204** may include a control module **240**, a transceiver **242**, a memory **244**, a display **246** and a charging connector **248**. The charging station **204** communicates with the vehicle **202** via the transceiver **242**. An electrical power line **250** is connected from the charging connector **248** to the charging connector **230** while charging the power source **210**. In one embodiment, the control module **240** communicates with, for example, a battery management module of the vehicle **202** to indicate to the battery management module, charging capabilities (e.g., maximum output voltage and current levels) of the charging station **204**. The charging station **204** may receive utility power and supply power at a predetermined voltage level to the vehicle **202** and/or the power source **210**. Prior to charging, the power source **210** is configured to be charged at the maximum output voltage level of the charging station **204**. The charging station **204** may be located in a residential building, at a business, at a roadside recharging station, at a public facility, and/or elsewhere.

(26) The charging station **204** may have a maximum output voltage rating of 400 volts (V), 800V or 1600V and have a nominal output voltage of, for example, 375V, 750V, or 1500V. The charging station **204** may have maximum output power ratings of 150 kilowatts (kW), 350 kW or 900 kW. A 1500V charging station may have a maximum output current rating of 600 amperes (A). The stated voltages, power levels, and current level are provided as examples only. The charging station **204** may have other voltage current and/or power ratings and outputs.

(27) The central monitoring station **206** may be located at a charging center along with the charging station **204** or may be located elsewhere. The central monitoring station **206** may be a service provider station, a central power station, or manufacturer monitoring station. The central monitoring station **206** may include a server **260**, which may in turn include a control module **262**, a transceiver **264** and memory **266**. The control module **262** may collect charging station capability information including maximum charging voltage and current levels and indicate the capabilities to vehicles, such as the vehicle **202**. The battery management module may then configure the power source **210** based on the capabilities of the charging station **204**.

(28) FIG. **3** shows a propulsion system **300** of a vehicle **302** that including a power source **303**

including a charging circuit **304** and battery packs **305**. The charging circuit **304** may be implemented as any of the charging circuits disclosed herein. The battery packs **305** may include any number of battery packs, such as the battery packs shown in FIGS. **4-7**.

(29) The power source **303** may supply power to an inverter **306**, which in turn drives a motor **308** (e.g., an interior permanent magnet (IPM) motor). Although the motor **308** is shown as an IPM motor, the motor **308** may be a surface permanent magnet motor or other type of electric motor. Although various examples are disclosed herein with respect to a motor, the examples are applicable to other electric machines.

(30) The power source **303** may include multiple cells and/or battery packs that are connected in series and/or in parallel to provide a predetermined voltage output. The cells and/or battery packs can be in a fixed configuration to be compatible with a particular type of charging station.

(31) The propulsion system **300** is used to move the vehicle **302** and further includes a shaft **310**, an axle **312** including a differential **314** and wheels **316**. The inverter **306** converts a DC voltage to a three-phase alternating current (AC) to power the motor **308**. The motor **308** rotates the shaft **310**, which in turn rotates the axle **312** via the differential **314**.

(32) The propulsion system **300** further includes a vehicle control module **320**, a propulsion control module **322** and a driver **324**. The vehicle control module **320** may generate a torque request signal. The torque request signal may be generated based on torque commanded, for example, by an accelerator **326** if included. The propulsion control module **322** may control the driver **324** based on the torque request signal. The driver **324** may, for example, generate pulse width modulation (PWM) signals to control states of transistors of the inverter **306** based on output of the propulsion control module **322**.

(33) The propulsion control module **322** controls the driver **324** based on outputs from sensors. The sensors may include current sensors (e.g., Hall Effect sensors **330**), a resolver **332**, a temperature sensor **334**, and/or other sensors **336** (e.g., an accelerometer). The current sensors may include sensors other than Hall Effect sensors.

(34) The propulsion control module **322** performs a transformation of current phase signals Ia, Ib and Ic for the three phases of the motor to current vector signals Id and Iq. The propulsion control module **322** determines how much current is flowing and how much current is needed (or requested) and modifies input current levels of the motor **308** by adjusting output current vector voltage signals supplied to the driver **324**. This is based on (i) the current vector signals Id, Iq, (ii) the position signal out of the resolver **332**, and (iv) the torque request signal from the vehicle control module **320**.

(35) A propulsion system **300** may include one or more electric motors. Each electric motor may be used to drive one or more axles and/or one or more wheels of the vehicle **302**. As an example, an electric motor may be used to drive an axle of the vehicle **302** via a differential. The vehicle control module **320**, based on a torque request, may signal the electric motor to rotate an input gear of the differential and as a result, the wheels attached to the axle. The vehicle control module **320** may adjust current, voltage and/or power levels of the electric motor to control acceleration, deceleration and/or speed of the vehicle **302**.

(36) The propulsion system **300** further includes a telematics module **338**, a battery management module **340** and power source sensors and/or status monitoring devices (referred to as power source sensors **342**). The battery management module **340** may configure the power source **303** as further described below based on output of the above-stated sensors, speed requests, current traveling speed, torque requests, charge states of battery packs of the power source **303**, etc. The power source sensors **342** may include voltage sensors, current sensors, and/or other circuit elements used to monitor VOCs, SOCs and/or capacities of the battery packs **305** and/or cells and/or modules of the battery packs **305**. The power source sensors **342** may be separate from the battery packs **305** or included in the battery packs **305** and monitor voltages, current levels, SOCs, VOCs, capacities, etc. of cells and/or modules of the battery packs and/or each of the battery packs

305 as a whole unit. The battery management module **340** may isolate one or more cells and/or battery packs **305** when: operating inappropriately; not charging to a predetermined voltage level; outputting a voltage and/or an amount of current at level(s) below predetermined minimum level(s); and/or exhibiting another abnormality. The modules **320**, **338**, **340**, and sensors **336** may be connected and/or communicate with each other via a network **360** or other form of communication.

(37) FIG. **4** shows a charging circuit **400** including charging port and DC-to-DC charging and/or charge balancing. The charging circuit **400** includes a charge port **402**, a contactor circuit **404**, an energy storage circuit **406**, and a DC-to-DC converter **408**, which may be connected to one or more DC loads **410**. The charge port **402** may be connected to a charging station, such as the charging station **204** of FIG. **2**.

(38) The contactor circuit **404** may include switches S**1**-S**3**, where S**2** is optional. The switches S**1** and S**3** have first terminals connected to a first terminal of the charge port **402**. The switch S**2** has a first terminal connected to a second terminal of the charge port **402**.

(39) The energy storage circuit **406** may include switches S**4**-S**8** and battery packs P**1** and P**2**. The switches S**4** and S**5** and the battery pack P**1** are connected in series. The switches S**6** and S**7** and the battery pack P**2** are connected in series. The switches S**4** and S**6** are connected to a second terminal of the switch S**1**. The switches S**5** and S**7** are connected to a second terminal of the switch S**2**. The switch S**8** has a first terminal connected to the switch S**4** and the battery pack P**1**. The switch S**8** has a second terminal connected to the battery pack P**2** and the switch S**7**.

(40) The DC-to-DC converter **408** may include a capacitor C**1** and a capacitor C**2**, transistor-diode pairs T**1**-T**4**, and an inductor L**1**. The capacitor C**1** is connected in parallel with the series combination of the switches S**6**, S**7** and the battery pack P**2**. The transistor-diode pairs T**1**, T**3** are connected in series and collectively in parallel with the capacitor C**1**. The transistor-diode pairs T**2**, T**4** are connected in series and collectively in parallel with the capacitor C**2**. The transistor-diode pair T**1** is connected to the second terminal of switch S**1** and first terminals of switches S**4** and S**6**. The transistor-diode pair T**2** is connected to a second terminal of the switch S**3**. The transistor-diode pairs T**3** and T**4** are connected to the second terminals of the switches S**2**, S**5** and S**7**. A first terminal of the inductor L**1** is connected to the transistor-diode pairs T**1**, T**3**. The second terminal of the inductor L**1** is connected to the transistor-diode pairs T**2**, T**4**. The DC-to-DC converter **408** is bidirectional. In a first direction, terminals of the capacitor C**1** and transistor-diode pairs T**1**, T**3** operate as inputs and terminals of the capacitor C**2** and transistor-diode pairs T**2**, T**4** operate as outputs. In a second direction, terminals of the capacitor C**1** and transistor-diode pairs T**1**, T**3** operate as outputs and terminals of the capacitor C**2** and the transistor-diode pairs T**2**, T**4** operate as inputs.

(41) The DC loads **410** may be connected in parallel via switches S**9**, S**10** to the series combination of the transistor-diode pairs T**2**, T**4**. The battery management module **412** or other control module disclosed herein may control states of the switches S**1**-S**10** and the transistors of the transistor-diode pairs T**1**-T**4**, as described herein.

(42) During operation, the battery packs P**1** and P**2** may be connected in series and the series combination thereof may be connected in parallel with the terminals of the charge port **402**. For example, switches S**1**, S**2**, S**5**, S**6** and S**8** may be closed and switches S**3**, S**4** and S**7** may be open. Switches S**9** and S**10** may be open during this period. This is referred to as "series charging". After series charging is completed, the DC-to-DC converter **408** may be used to charge the one of the battery packs P**1**, P**2** that has the lowest SOC and/or VOC. This may be referred to as "isolated charging". For example, if battery pack P**1** has the lowest VOC, then switches S**1**, S**2**, S**6**, S**7** and S**8** are open and switches S**3**, S**4** and S**5** are closed. This allows the charge port **402** to charge battery pack P**1** via the DC-to-DC converter **408**. Switches S**9** and S**10** may be open during this period. When the VOCs of the battery packs were within a predetermined range of each other, isolated charging is complete. After isolated charging, switches S**1**, S**2**, S**3** and S**8** are open and

switches S**4**, S**5**, S**6**, S**7**, S**9** and S**10** are closed, such that the battery packs P**1**, P**2** are connected in parallel and supplying power to the DC-to-DC converter **408**, which is supplying power to the DC loads **410**.

(43) The battery management module **412** may control duty cycles and/or frequencies of pulse width modulated (PWM) signals supplied to the transistors of the transistor-diode pairs T**1**-T**4**. The duty cycles and frequencies may be adjusted to adjust the output voltage of the DC-to-DC converter **408**. For example, the duty cycles and/or frequencies are different when outputting a high voltage as compared to outputting a low voltage. This control may be provided based on monitored SOC, VOC and/or capacity states of the battery packs P**1** and P**2**.

(44) FIG. **5** shows a charging circuit **500** configured for charge balancing between battery packs via a DC-to-DC converter. The charging circuit **500** includes a charge port **502**, a contactor circuit **504**, an energy storage circuit **506**, and a DC-to-DC converter **508**, which may be connected to one or more DC loads **510**. The charge port **502** may be connected to a charging station, such as the charging station **204** of FIG. **2**. The contactor circuit **504** may include switches S**1**, S**2**. The switches S**1** and S**2** have first terminals connected respectively to terminals of the charge port **502**.

(45) The energy storage circuit **506** may include switches S**4**-S**9** and battery packs P**1** and P**2**. The switches S**4** and S**5** and the battery pack P**1** are connected in series. The switches S**6** and S**7** and the battery pack P**2** are connected in series. The switches S**4** and S**6** are connected to a second terminal of the switch S**1**. The switches S**5** and S**7** are connected to a second terminal of the switch S**2**. The switch S**8** has a first terminal connected to the switch S**4** and the battery pack P**1**. The switch S**8** has a second terminal connected to the battery pack P**2** and the switch S**7**. The switch S**9** has a first terminal connected to the second terminal of the switch S**1** and first terminals of the switches S**3** and S**4**. The switch S**9** has a second terminal connected to a first terminal of the switch S**6**.

(46) The DC-to-DC converter **508** may include capacitors C**1** and C**2**, transistor-diode pairs T**1**-T**4**, and an inductor L**1**. The capacitor C**1** is connected in parallel with the series combination of the switches S**6**, S**7** and the battery pack P**2**. The transistor-diode pairs T**1**, T**3** are connected in series and collectively in parallel with the capacitor C**1**. The transistor-diode pairs T**2**, T**4** are connected in series and collectively in parallel with the capacitor C**2**. The transistor-diode pair T**1** is connected to the second terminal of switch S**9** and a first terminal of switch S**6**. The transistor-diode pair T**2** is connected to a second terminal of the switch S**3**. The transistor-diode pair T**3** is connected to the second terminals of the switches S**2**, S**5** and S**7**. The transistor-diode pair T**4** is connected to second terminals of the switches S**2**, S**5**, S**7**. A first terminal of the inductor L**1** is connected to the transistor-diode pairs T**1**, T**3**. The second terminal of the inductor L**1** is connected to the transistor-diode pairs T**2**, T**4**. The DC-to-DC converter **508** is bidirectional. In a first direction, terminals of the capacitor C**1** and transistor-diode pairs T**1**, T**3** operate as inputs and terminals of the capacitor C**2** and transistor-diode pairs T**2**, T**4** operate as outputs. In a second direction, terminals of the capacitor C**1** and transistor-diode pairs T**1**, T**3** operate as outputs and terminals of the capacitor C**2** and transistor-diode pairs T**2**, T**4** operate as inputs.

(47) The DC loads **510** may be connected in parallel via switches S**10**, S**11** to the series combination of the transistor-diode pairs T**2**, T**4**. The battery management module **512** or other control module disclosed herein may control states of the switches S**1**-S**11** and the transistors of the transistor-diode pairs T**1**-T**4**, as described herein.

(48) During operation, the battery packs P**1** and P**2** may be connected in series and the series combination thereof may be connected in parallel with the terminals of the charge port **402**. For example, switches S**1**, S**2**, S**5**, S**6**, S**8** and S**9** may be closed and switches S**3**, S**4** and S**7** may be open. Switches S**10** and S**11** may be open during this period. After series charging is completed, the DC-to-DC converter **508** may be used to charge balance the battery packs P**1**, P**2**. The battery pack that has the lowest SOC and/or VOC may be charged by the other battery pack. For example, switches S**1**, S**2**, S**8** and S**9** are open and switches S**3**, S**4**, S**5**, S**6** and S**7** are closed. This disconnects the charge port and connects the first battery pack P**1** to the transistor-diode pairs T**2**,

T**4** and the second battery pack P**2** to the transistor-diode pairs T**1** and T**3**.

(49) The battery management module **512** may control duty cycles and/or frequencies of pulse width modulated (PWM) signals supplied to the transistors of the transistor-diode pairs T**1**-T**4**. The duty cycles and frequencies may be adjusted to adjust the output voltage of the DC-to-DC converter **508**. This control may be provided based on monitored SOC, VOC and/or capacity states of the battery packs P**1** and P**2**.

(50) When the VOCs of the battery packs P**1**, P**2** are within a predetermined range of each other, charge balancing is complete. After charge balancing, switches S**1**, S**2**, S**3** and S**8** are open and switches S**4**, S**5**, S**6**, S**7**, S**9**, S**10** and S**11** are closed, such that the battery packs P**1** and P**2** are connected in parallel and supplying power to the DC-to-DC converter **508**, which is supplying power to the DC loads **510**.

(51) FIG. **6** shows a charging circuit **600** configured for independent charging and/or charge balancing of battery packs P**1**, P**2** via respective charge ports **602**, **603**. The charging circuit **600** also includes a contactor circuit **604**, an energy storage circuit **606**, and a DC-to-DC converter **608**, which may be connected to one or more DC loads **610**. The charge ports **602**, **603** may be connected to a charging station, such as the charging station **204** of FIG. **2**. The contactor circuit **604** may include switches S**1**, S**2**, S**10**, S**11**. The switches S**1**, S**2**, S**10**, S**11** have first terminals connected to corresponding terminals of the charge port **602**, **603**.

(52) The energy storage circuit **606** may include switches S**4**-S**9** and battery packs P**1** and P**2**. The switches S**4** and S**5** and the battery pack P**1** are connected in series. The switches S**6** and S**7** and the battery pack P**2** are connected in series. The switches S**4** and S**6** are connected to a second terminal of the switch S**1** and a first terminal of switch S**3**. The switches S**5** and S**7** are connected to a second terminal of the switch S**2**. The switch S**6** is connected to a second terminal of the switch S**9**. The switch S**7** is connected to second terminals of the switches S**2** and S**11**.

(53) The switch S**8** has a first terminal connected to the switch S**4** and the battery pack P**1**. The switch S**8** has a second terminal connected to the battery pack P**2** and the switch S**7**. The switch S**9** has a first terminal connected to the second terminal of the switch S**1** and first terminals of the switches S**3** and S**4**. The second terminal of the switch S**9** is connected to the second terminal of the switch S**10**.

(54) The DC-to-DC converter **608** may include capacitors C**1** and C**2**, transistor-diode pairs T**1**-T**4**, and an inductor L**1**. The capacitor C**1** is connected in parallel with the series combination of the switches S**6**, S**7** and the battery pack P**2**. The transistor-diode pairs T**1**, T**3** are connected in series and collectively in parallel with the capacitor C**1**. The transistor-diode pairs T**2**, T**4** are connected in series and collectively in parallel with the capacitor C**2**. The transistor-diode pair T**2** is connected to a second terminal of the switch S**3**. The transistor-diode pair T**4** is connected to a second terminals of the switches S**2** and S**11**.

(55) A first terminal of the inductor L**1** is connected to the transistor-diode pairs T**1**, T**3**. The second terminal of the inductor L**1** is connected to the transistor-diode pairs T**2**, T**4**. The DC-to-DC converter **608** is bidirectional. In a first direction, terminals of the capacitor C**1** and transistor-diode pairs T**1**, T**3** operate as inputs and terminals of the capacitor C**2** and transistor-diode pairs T**2**, T**4** operate as outputs. In a second direction, terminals of the capacitor C**1** and transistor-diode pairs T**1**, T**3** operate as outputs and terminals of the capacitor C**2** and transistor-diode pairs T**2**, T**4** operate as inputs.

(56) The DC loads **610** may be connected in parallel via switches S**12**, S**13** to the series combination of the transistor-diode pairs T**2**, T**4**. The battery management module **612** or other control module disclosed herein may control states of the switches S**1**-S**13** and the transistors of the transistor-diode pairs T**1**-T**4**, as described herein.

(57) During operation, the battery packs P**1** and P**2** may be connected in series and the series combination thereof may be connected in parallel with the terminals of each of the charge ports **602**, **603**. For example, (i) switches S**1** and S**2** and/or S**10** and S**11** may be closed, (ii) switches S**5**,

S**6**, S**8** and S**9** may be closed, and (iii) switches S**3**, S**4** and S**7** may be open. Switches S**12** and S**13** may be open during this period.

(58) The battery packs P**1** and P**2** may also be connected individually to each of the charge ports **602**, **603**. For example, switches S**4**, S**5**, S**9**, S**10** and S**11** may be closed to connect the charge port **602** to the battery pack P**1**. The switches S**6**, S**7**, S**10** and S**11** may be closed to connect the charge port **602** to the battery pack P**2**. The switches S**1**, S**2**, S**3** and S**4** may be closed to connect the charge port **603** to the battery pack P**1**. The switches S**1**, S**2**, S**6**, S**7** and S**9** may be closed to connect the charge port **603** to the battery pack P**2**.

(59) The battery packs P**1** and P**2** may also be connected in parallel and connected to the charge port **602** and/or **603**. Switches S**1**, S**2**, S**4**, S**5**, S**6**, S**7**, S**9** may be closed to connect the charge port **603** to the battery packs P**1** and P**2** connected in parallel. Switches S**4**, S**5**, S**6**, S**7**, S**9**, S**10** and S**11** may be closed to connect the charge port **602** to the battery packs P**1** and P**2** connected in parallel. Switches S**1**, S**2**, S**4**, S**5**, S**6**, S**7**, S**9**, S**10** and S**11** are closed when connecting both of the charge ports to the battery packs P**1** and P**2** connected in parallel. This state configuration allows for multi-port and/or independent charging of the battery packs P**1**, P**2** via the charge ports **602**, **603**.

(60) After series charging, multi-port charging, and/or isolated charging is completed, the one of the battery packs with a lower charge than the other one of the battery packs may be (i) charged by one or more of the charge ports **602**, **603**, or (ii) charged by the battery pack with the higher state of charge via the DC-to-DC converter **608**.

(61) The DC-to-DC converter **608** may be used to charge balance the battery packs P**1**, P**2**. The battery pack that has the lowest SOC and/or VOC may be charged by the other battery pack. For example, switches S**1**, S**2**, S**8**, S**9**, S**10** and S**11** are open and switches S**3**, S**4**, S**5**, S**6** and S**7** are closed. This disconnects the charge port **602**, **603** and connects the first battery pack P**1** to the transistor-diode pairs T**2**, T**4** and the second battery pack P**2** to the transistor-diode pairs T**1** and T**3**.

(62) The battery management module **612** may control duty cycles and/or frequencies of pulse width modulated (PWM) signals supplied to the transistors of the transistor-diode pairs T**1**-T**4**. The duty cycles and frequencies may be adjusted to adjust the output voltage of the DC-to-DC converter **608**. This control may be provided based on monitored SOC, VOC and capacity states of the battery packs P**1** and P**2**.

(63) When the VOCs of the battery packs P**1**, P**2** are within a predetermined range of each other, charge balancing is complete. After charge balancing, switches S**1**, S**2**, S**3**, S**8**, S**10** and S**11** are open and switches S**4**, S**5**, S**6**, S**7**, S**9**, S**12** and S**13** are closed, such that the battery packs P**1** and P**2** are connected in parallel and supplying power to the DC-to-DC converter **608**, which is supplying power to the DC loads **610**.

(64) FIG. **7** a charging circuit **700** configured for independent charging and/or charge balancing of battery packs P**1** and P**2** via respective charge ports **702**, **703** and a motor inverter circuit **708**. The charging circuit **700** also includes a contactor circuit **704**, an energy storage circuit **706**, and the motor inverter circuit **708**. The charge ports **702**, **703** may be connected to a charging station, such as the charging station **204** of FIG. **2**. The contactor circuit **704** may include switches S**1**, S**2**, S**10**, S**11**. The switches S**1**, S**2**, S**10**, S**11** have first terminals connected to corresponding terminals of the charge port **702**, **703**.

(65) The energy storage circuit **706** may include switches S**4**-S**9** and battery packs P**1** and P**2**. The switches S**4** and S**5** and the battery pack P**1** are connected in series. The switches S**6** and S**7** and the battery pack P**2** are connected in series. The switches S**4** and S**6** are connected to a second terminal of the switch S**1** and a first terminal of switch S**3**. The switches S**5** and S**7** are connected to a second terminal of the switch S**2**. The switch S**6** is connected to a second terminal of the switch S**9**. The switch S**7** is connected to second terminals of the switches S**2** and S**11**.

(66) The switch S**8** has a first terminal connected to the switch S**4** and the battery pack P**1**. The switch S**8** has a second terminal connected to the battery pack P**2** and the switch S**7**. The switch S**9** has a first terminal connected to the second terminal of the switch S**1** and first terminals of the

switches S**3** and S**4**. The second terminal of the switch S**9** is connected to the second terminal of the switch S**10**.

(67) The motor inverter circuit **708** includes a capacitor C**1**, an inverter **709** and a motor **710** including inductors (or coils) L**1**-L**3**. The inverter includes transistor-diode pairs T**1**-T**6**. The capacitor C**1** is connected in parallel with the series combination of the switches S**6**, S**7** and the battery pack P**2**. The transistor-diode pairs T**1**, T**4** are connected in series and collectively in parallel with the capacitor C**1**. The transistor-diode pairs T**2**, T**5** are connected in series and in parallel with the series combination of transistor-diode pairs T**1**, T**4**. The transistor-diode pairs T**3**, T**6** are connected in series and in parallel with the series combination of transistor-diode pairs T**1**, T**4** and the series combination of transistor-diode pairs T**2**, T**5**. The transistor-diode pairs T**1**, T**2** and T**3** are connected to second terminals of the switches S**9** and S**10** and to the first terminal of switch S**6**. The transistor-diode pairs T**4**, T**5** and T**6** are connected to a second terminals of the switches S**2**, S**5**, S**7** and S**11**.

(68) A first terminal of the inductor L**1** is connected to the transistor-diode pairs T**1** and T**4** and a second terminal of the inductor L**1** is connected to the second terminal of the switch S**3**. A first terminal of the inductor L**2** is connected to the transistor-diode pairs T**2** and T**5** and a second terminal of the inductor L**2** is connected to the second terminal of the switch S**3**. A first terminal of the inductor L**3** is connected to the transistor-diode pairs T**3** and T**6** and a second terminal of the inductor L**3** is connected to the second terminal of the switch S**3**.

(69) Current flow through the motor inverter circuit **708** may be bidirectional. In a first direction, terminals of the capacitor and transistor-diode pairs T**1**-T**6** operate as inputs and second terminals of the inductors L**1**-L**3** operate as outputs. In a second direction, terminals of the capacitor and transistor-diode pairs T**1**-T**6** operate as outputs and second terminals of the inductors L**1**-L**3** operate as inputs.

(70) The battery management module **712** or other control module disclosed herein may control states of the switches S**1**-S**11** and the transistors of the transistor-diode pairs T**1**-T**6**, as described herein.

(71) During operation, the battery packs P**1** and P**2** may be connected in series and the series combination thereof may be connected in parallel with the terminals of each of the charge ports **702**, **703**. For example, (i) switches S**1** and S**2** and/or S**10** and S**11** may be closed, (ii) switches S**5**, S**6**, S**8** and S**9** may be closed, and (iii) switches S**3**, S**4** and S**7** may be open. Switches S**12** and S**13** may be open during this period.

(72) The battery packs P**1** and P**2** may also be connected individually to each of the charge ports **702**, **703**. For example, switches S**4**, S**5**, S**9**, S**10** and S**11** may be closed to connect the charge port **702** to the battery pack P**1**. The switches S**6**, S**7**, S**10** and S**11** may be closed to connect the charge port **702** to the battery pack P**2**. The switches S**1**, S**2**, S**3** and S**4** may be closed to connect the charge port **703** to the battery pack P**1**. The switches S**1**, S**2**, S**6**, S**7** and S**9** may be closed to connect the charge port **703** to the battery pack P**2**.

(73) The battery packs P**1** and P**2** may also be connected in parallel and connected to the charge port **702** and/or **703**. Switches S**1**, S**2**, S**4**, S**5**, S**6**, S**7**, S**9** may be closed to connect the charge port **703** to the battery packs P**1** and P**2** connected in parallel. Switches S**4**, S**5**, S**6**, S**7**, S**9**, S**10** and S**11** may be closed to connect the charge port **702** to the battery packs P**1** and P**2** connected in parallel. Switches S**1**, S**2**, S**4**, S**5**, S**6**, S**7**, S**9**, S**10** and S**11** are closed when connecting both of the charge ports to the battery packs P**1** and P**2** connected in parallel. This state configuration allows for multi-port and/or independent charging of the battery packs P**1**, P**2** via the charge ports **702**, **703**.

(74) After series charging, multi-port charging, and/or isolated charging is completed, the one of the battery packs with a lower charge than the other one of the battery packs may be (i) charged by one or more of the charge ports **702**, **703**, (ii) charged by the battery pack with the higher state of charge via the motor inverter circuit **708**, and/or (iii) via the motor inverter circuit **708**, which may operate as a buck or boost converter to charge the battery pack with the lower VOC. When the

battery pack P**2** has a higher VOC and/or SOC, the battery pack P**1** may be charged by one or more of the charge ports **702**, **703** or by the battery pack P**2**. For example, the switches S**1**, S**2**, S**6**, S**7**, S**8** and S**9** may be open and the switches S**3**, S**4**, S**5**, S**10** and S**11** may be closed for charging the battery pack P**1** via the motor inverter circuit **708**. In this configuration, charge port **702** and the motor inverter circuit **708** are used to charge the battery pack P**1**. As another example, switches S**1**, S**2**, S**8**, S**9**, S**10** and S**11** are open and switches S**3**, S**4**, S**5**, S**6** and S**7** are closed, such that the battery pack P**2** is charging the battery pack P**1** via the motor inverter circuit **708**.

(75) The motor inverter circuit **708** may be used to charge balance the battery packs P**1**, P**2**. The battery pack that has the lowest SOC and/or VOC may be charged by the other battery pack. For example, switches S**1**, S**2**, S**8**, S**9**, S**10** and S**11** are open and switches S**3**, S**4**, S**5**, S**6** and S**7** are closed. This disconnects the charge port **702**, **703** and connects the first battery pack P**1** to the second terminals of the inductors L**1**-L**3** of the motor **710** and the second battery pack P**2** to the transistor-diode pairs T**1**-T**6**.

(76) The battery management module **712** may control duty cycles and/or frequencies of pulse width modulated (PWM) signals supplied to the transistors of the transistor-diode pairs T**1**-T**6**. The duty cycles and frequencies may be adjusted to adjust the output voltage of the inverter **709** and thus the output voltage of the motor inverter circuit **708**. This control may be provided based on monitored SOC, VOC and/or capacity states of the battery packs P**1** and P**2**.

(77) When the VOCs of the battery packs P**1**, P**2** are within a predetermined range of each other, charge balancing is complete. After charge balancing, switches S**1**, S**2**, S**3**, S**8**, S**10** and S**11** are open and switches S**4**, S**5**, S**6**, S**7** and S**9** are closed, such that the battery packs P**1** and P**2** are connected in parallel and supplying power to the motor inverter circuit **708**. The motor **710** may be used for propulsion purposes.

(78) FIG. **8** shows an example plot of an open circuit voltage (VOC) versus state of charge (SOC) curve **800**. As the SOC increases, the VOC increases. This is not a linear relationship. A VOC of a battery pack, module, and/or cell may be calculated based on a SOC of that battery pack, module and/or cell. In one embodiment, when the vehicle control module **320** of FIG. **3** calculates VOCs of battery pack modules, a VOC versus SOC curve, such as the plot of FIG. **8** may be used. When the battery management module **340** of FIG. **3** calculates VOCs of the battery pack modules, each battery pack module calculate its own VOC based on a respective VOC versus SOC curve. A VOC of the corresponding battery pack may be set equal to a sum of the VOCs of the battery pack modules of that battery pack. Module based VOC calculation can improve the accuracy of determined VOCs.

(79) When a battery pack has aged, a corresponding capacity of that battery pack is limited and as much the battery pack is referred to as being "weak". A weak battery pack stores less charge than a "strong" or "stronger" battery pack. A large in-rush current may be generated when the weak battery pack is connected in parallel with the strong battery pack. This can be true, even when the weak battery pack is fully charged. To overcome this issue, during charging, the VOC and/or SOC of the weak battery pack is monitored. High-voltage (e.g., 800V) series charging is stopped when the VOC and/or SOC of the weak battery pack reaches respective predetermined limits. As a couple of examples, the SOC limit may be 90% or 98%. One limit may be used, since the VOC and SOC of a battery pack are related.

(80) A weak battery pack, which has a smaller capacity, typically charges quicker than a strong battery pack and typically has a higher VOC than the strong battery pack. If a battery pack is charged over defined SOC and VOC limits, then an unsafe and/or thermal runaway condition can arise. Since the weak battery pack is charged fully and/or charge to a VOC and/or SOC limit, then control as described herein prevents the strong battery pack from further charging the weak battery pack. This may be handled by, for example, either of the control modules **320**, **340** of FIG. **3**. The strong battery pack has room to accept some more charge. When the battery packs are connected in parallel, the battery packs balance out and the SOC of the weak battery pack decreases due to the

charging of the strong battery pack via the weak battery pack. The SOC of the strong battery pack increases slightly due to this charging. The resulting SOCs of the battery packs are then within a safe operating range.

(81) FIG. **9** shows an example charging method implemented by a control module, such as the vehicle control module **320** or battery management module **340** of FIG. **3** or other control module disclosed herein. Although the following operations are primarily described with respect to the implementations of FIGS. **4**-**7**, the operations may be easily modified to apply to other implementations of the present disclosure. The operations may be iteratively performed by one of the disclosed battery management modules. Also, although the following operations are primarily described with respect to the embodiments of FIGS. **4**-**7**, the operations may be applied to application that include more than two battery packs.

(82) The method may begin at **900**. At **902**, the control module may determine the VOCs, SOCs and/or capacities of battery packs (e.g., the battery packs of FIGS. **3**-**7**) of a vehicle. This may be determined as described above. When the VOCs and/or SOCs are below predetermined thresholds, operation **904** may be performed. Operation **904** may be performed when the control module receives an indication and/or an instruction to initiate charging and/or charge balancing.

(83) At **904**, the control module may determine whether a charging circuit (e.g., one of the charging circuits of FIGS. **2**-**7**) of the vehicle is connected to shore power (i.e., connected to a charging station). The control module may communicate with the charging station (e.g., the charging station **204** of FIG. **2**) and/or other infrastructure device to determine charging parameters (e.g., voltage and/or current levels). If the charging circuit is connected to a charging station, operation **906** may be performed, otherwise operation **916** may be performed. Operations **906** and **916** may be performed for example when the charging circuit is connected to a charging station and the VOCs and/or SOCs of one or more of the battery packs are below predetermined maximum values.

(84) At **906**, the control module may determine whether multiple battery packs are to be charged. If yes, operation **908** may be performed, otherwise operation **914** may be performed.

(85) At **908**, the control module may determine whether independent battery pack charging is to be performed. If yes, operation **910** may be performed, otherwise operation **912** may be performed. At **910**, the control module may connect the battery packs to respective charge ports, such as the charge ports of FIGS. **6**-**7**. At **912**, the control module may connect the battery packs in series and to one or more charge ports, such as any of the charge ports of FIGS. **4**-**7**. At **914**, the control module may connect the battery pack to be charged to one or more charge ports, such as any of the charge ports of FIGS. **4**-**7**.

(86) At **916**, the control module may determine whether charge balancing is to be performed. If yes, operation **918** is performed, otherwise operation **902** may be performed. At **918**, the control module may determine whether charge balancing is to be performed via a DC-to-DC converter (e.g., one of the DC-to-DC converters of FIGS. **4**-**6**). If yes, operation **920** may be performed, otherwise operation **926** may be performed.

(87) At **920**, the control module may determine whether charge balancing using a charge port is to be performed. If yes, operation **922** may be performed, otherwise operation **924** may be performed. At **922**, the control module may connect a first battery pack to a charge port and connect a second battery pack to the DC-to-DC converter, as described above. At **924**, the control module may connect the first battery pack to first side (i.e., input or output) of DC-to-DC converter and second battery pack to second side (i.e., other one of the input and output) of DC-to-DC converter.

(88) At **926**, the control module may determine whether to perform charge balancing via a motor inverter circuit, such as the motor inverter circuit of FIG. **7**. If yes, operation **928** may be performed, otherwise operation **934** may be performed.

(89) At **928**, the control module may determine whether charge balancing using a charge port is to be performed. If yes, operation **930** may be performed, otherwise operation **932** may be performed.

(90) At **930**, the control module may connect the first battery pack to one or more charge ports and

the second battery pack to the motor inverter circuit. At **932**, the control module may connect the first battery pack a first side of the motor inverter circuit and the second battery pack to a second side of the motor inverter circuit. At **934**, the control module may connect the battery packs in parallel.

(91) The above-described operations of FIG. **9** are meant to be illustrative examples. The operations may be performed sequentially, synchronously, simultaneously, continuously, during overlapping time periods or in a different order depending upon the application. Also, any of the operations may not be performed or may be skipped depending on the implementation and/or sequence of events.

(92) The above-described examples include use of DC-to-DC converters and motor inverter circuit to charge balance the VOCs of battery packs. This charge balancing may be performed subsequent to series charging the battery packs. A first battery pack with a low VOC may be continuously charged until the VOC of the first battery pack is within a predetermined range of a VOC of at least one other battery pack and/or a difference between the two VOCs is less than a predetermine threshold. When the stated charge balancing is completed, and battery packs may be connected in parallel. The charging of the battery pack having the low VOC may be accomplished using one or more the above-stated charge ports to continuously charge the low VOC battery pack. As an alternative, a battery pack having a high VOC may be used to charge the battery pack having the low VOC.

(93) 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.

(94) 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."

(95) 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.

(96) 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.

(97) 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.

(98) 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.

(99) 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).

(100) 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.

(101) 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.

(102) 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 charging system comprising: one or more charge ports configured to receive shore power from a charging station; at least one of a direct current (DC)-to-DC converter or a motor inverter circuit; a plurality of switches configured to connect a plurality of battery packs (i) to the charging station via the one or more charge ports and (ii) to the at least one of the DC-to-DC converter or the motor inverter circuit; a control module configured to (i) determine at least one of open circuit voltages or states of charges of the plurality of battery packs, (ii) based on the at least one of the open circuit voltages or the states of charges of the plurality of battery packs, determine whether to connect at least one of the plurality of battery packs to the one or more charge ports, the DC-to-DC converter, and the motor inverter circuit, and (iii) based on the determination of whether to connect the at least one of the plurality of battery packs, control states of the plurality of switches to charge the at least one of the plurality of battery packs by selectively connecting the at least one of the plurality of battery packs to at least one of (a) the one or more charge ports, or (b) the at least one of the DC-to-DC converter or the motor inverter circuit; and a contactor circuit connected between i) the one or more charge ports and ii) the plurality of battery packs and the DC-to-DC converter, wherein the plurality of battery packs comprise a first battery pack and a second battery pack, the plurality of switches comprise a first switch, a second switch, a third switch, a fourth switch, and a fifth switch, the first switch is connected between the contactor circuit and the first battery pack, the second switch connected between the first battery pack and the contactor circuit, the third switch is connected between the contactor circuit and the second battery pack, the fourth switch is connected between the second battery pack and the contactor circuit, and the fifth switch is connected between i) the first switch and the first battery pack and ii) the second battery pack and the fourth switch.

2. The charging system of claim 1, further comprising a plurality of sensors configured to detect the open circuit voltages of the plurality of battery packs.

3. The charging system of claim 1, wherein: the plurality of switches are configured to connect the one or more charge ports to the plurality of battery packs; and the control module is configured to, based on the at least one of the open circuit voltages or the states of charges of the plurality of battery packs, control the states of the plurality of switches to charge at least one of the plurality of battery packs by selectively connecting the at least one of the plurality of battery packs to the one or more charge ports.

4. The charging system of claim 1, wherein: the charging system comprises the DC-to-DC converter; the plurality of switches are configured to connect the one or more charge ports and the DC-to-DC converter to the plurality of battery packs; and the control module is configured, based on the at least one of the open circuit voltages or the states of charges of the plurality of battery packs, to control the states of the plurality of switches to charge the at least one of the plurality of battery packs by selectively connecting the at least one of the plurality of battery packs to the DC-to-DC converter.

5. The charging system of claim 4, wherein the control module is configured to control the states of the plurality of switches to charge a selected one or more of the plurality of battery packs via the one or more charge ports and the DC-to-DC converter.

6. The charging system of claim 1, wherein: the plurality of switches are configured to connect the motor inverter circuit to the plurality of battery packs; and the control module is configured to,

based on the at least one of the open circuit voltages or the states of charges of the plurality of battery packs, control the states of the plurality of switches to charge at least one of the plurality of battery packs by selectively connecting the at least one of the plurality of battery packs to the motor inverter circuit.

7. The charging system of claim 6, wherein the control module is configured to control the states of the plurality of switches to charge a selected one or more of the plurality of battery packs via the one or more charge ports and the motor inverter circuit.

8. The charging system of claim 6, wherein the motor inverter circuit comprises: an inverter; and a motor configured to receive power from the plurality of battery packs or the one or more charge ports via the inverter.

9. The charging system of claim 1, wherein the control module is configured to: control the states of the plurality of switches to connect (i) the plurality of battery packs in series and to terminals of the one or more charge ports; and change the states of the plurality of switches to connect the one or more charge ports to an input of the DC-to-DC converter, and (ii) an output of the DC-to-DC converter to one or more of the plurality of battery packs.

10. The charging system of claim 1, wherein the control module is configured to control the states of the plurality of switches to (i) connect the first battery pack to an input of the DC-to-DC converter, and (ii) an output of the DC-to-DC converter to the second battery pack to perform charge balancing via the DC-to-DC converter.

11. The charging system of claim 1, wherein: the one or more charge ports comprise a plurality of charge ports; each of the plurality of charge ports are configured to be connected to each of the plurality of battery packs based on states of the plurality of switches; and the control module is configured to independently charge each of the plurality of battery packs with one or more of the plurality of charge ports.

12. The charging system of claim 1, wherein the control module is configured to: control the states of the plurality of switches to series charge the plurality of battery packs; and subsequent to series charging the plurality of battery packs, cease charging of a first one of the plurality of battery packs and continue charging of a second one of the battery packs until an open circuit voltage of the second one of the plurality of battery packs is within a predetermined range of an open circuit voltage of the first one of the plurality of battery packs.

13. The charging system of claim 12, wherein the charging of the second one of the plurality of battery packs is performed via the at least one of the DC-to-DC converter or the motor inverter circuit.

14. The charging system of claim 13, wherein subsequent to charging the second one of the plurality of battery packs, the control module is configured to control states of the plurality of switches to connect the plurality of battery packs in parallel.

15. The charging system of claim 1, wherein the control module is configured to calculate an open circuit voltage of one of the plurality of battery packs based on open circuit voltages of a plurality of modules of the one of the plurality of battery packs.

16. The charging system of claim 1, wherein the control module is configured to subsequent to series charging the plurality of battery packs, determine a first one of the plurality of battery packs has a lower capacity and a higher open circuit voltage than a second one of the plurality of battery packs, and charge the second one of the plurality of battery packs via the first one of the plurality of battery packs.

17. The charging system of claim 1, wherein the charging of the second one of the plurality of battery packs is performed via the at least one of the DC-to-DC converter or the motor inverter circuit.

18. The charging system of claim 1, wherein the control module is configured, subsequent to the charging of at least one of the plurality of battery packs, to at least one of: control the states of the plurality of switches to (i) connect the plurality of battery packs in parallel and to an input of the

DC-to-DC converter, and (ii) connect an output of the DC-to-DC converter to a load; or control the states of the plurality of switches to connect the plurality of battery packs in parallel and to an input of the motor inverter circuit to drive a motor of the motor inverter circuit.

19. The charging system of claim 1, wherein the control module is configured to (i) determine the open circuit voltages of the plurality of battery packs, (ii) based on the open circuit voltages of the plurality of battery packs, determine whether to connect the at least one of the plurality of battery packs to the one or more charge ports, the DC-to-DC converter, and the motor inverter circuit, and (iii) based on the determination of whether to connect the at least one of the plurality of battery packs to the one or more charge ports, the DC-to-DC converter, and the motor inverter circuit, control states of the plurality of switches to charge the at least one of the plurality of battery packs by selectively connecting the at least one of the plurality of battery packs to at least one of (a) the one or more charge ports and (b) the DC-to-DC converter or the motor inverter circuit.

20. The charging system of claim 1, further comprising a sixth switch configured to bypass the plurality of switches and the DC-to-DC converter and connect the one or more charge ports to one or more loads.

21. The charging system of claim 1, wherein: the one or more charge ports comprise a plurality of charge ports; and the contact circuit is configured to independently connect each of the plurality of charge ports to each of the plurality of battery packs and the DC-to-DC converter.