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Low-cost balancing control for distributed low voltage system with bi-directional converters to support multiple low voltage busses

Abstract

A vehicle includes an electrical system for balancing a state of charge in a battery pack. The electrical system includes a plurality of module groups. A switch array includes a plurality of switches. Each switch is coupled to a respective module group. The switch can be in one of a first state that connects the module group to a first low voltage bus, a second state that connects the module group to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus. The array is placed in a first phase of a mode of operation with at least one switch in one of the first state and the second state and cycles through the phases of the mode to balance a charge between the plurality of module groups.

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Background/Summary

INTRODUCTION

(1) The subject disclosure relates to an electrical system in a vehicle and, in particular, to a system and method for balancing the state of charge between battery modules of a battery pack of the vehicle by controlling a configuration of switches between the battery pack and one or more low voltage loads of the vehicle.

(2) An electric vehicle operates using an electric system having a battery pack. The battery pack includes a plurality of module groups, each module group having a plurality of battery modules. The battery pack provides power both to high voltage loads, such as the motor, etc. and low voltage loads, such as radio, dashboard, etc. During operation, the state of charge of each module group can vary, causing divergence between the states of charge across the module groups of the battery pack. As the states of charge diverge, the operation of the electric system declines. Accordingly, it is desirable to provide a system and method for balancing the states of charge across the plurality of module groups.

SUMMARY

(3) In one exemplary embodiment, a method of balancing a state of charge between module groups of a battery pack of a vehicle is disclosed. For each module group, the module group is connected to a respective switch of a switch array, wherein the respective switch is configured to be in one of a first state in which the module group is connected to a first low voltage bus, a second state in which the module group is connected to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus. The switch array is placed in a configuration with at least one switch in one of the first state and the

second state, wherein the configuration defines a first phase of a mode of operation of the switch array. The mode is cycled through to balance the state of charge between the module groups.
(4) In addition to one or more of the features described herein, the method further includes adjusting duration of a phase of the mode to passively balance the state of charge between the module groups.
(5) In addition to one or more of the features described herein, the method further includes changing the mode of operation of the switch array.
(6) In addition to one or more of the features described herein, a module group includes a plurality of battery modules, further including connecting each battery module of the module group to the respective switch via a unidirectional direct current (DC/DC) converter.
(7) In addition to one or more of the features described herein, wherein cycling through the mode further includes performing a cyclic permutation of the configurations of the switch array.
(8) In addition to one or more of the features described herein, the respective switch is one of a single switch and a switch pair including a first switch for controlling the connection to the first low voltage bus and a second switch for controlling the connection to the second low voltage bus.
(9) In addition to one or more of the features described herein, wherein the module groups include at least three module groups.
(10) In another exemplary embodiment, an electrical system for a vehicle is disclosed. The electrical system includes a plurality of module groups, a switch array and a processor. The switch array includes a plurality of switches, each switch coupled to a module group from the plurality of module groups and configured to be in one of a first state that connects the module group to a first low voltage bus, a second state that connects the module group to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus. The processor is configured to place the switch array in a configuration with at least one switch in one of the first state and the second state, wherein the configuration defines a first phase of a mode of operation of the switch array, and cycle through the mode to balance a state of charge between the plurality of module groups.
(11) In addition to one or more of the features described herein, the processor is further configured to adjust a duration of a phase of the mode to passively balance the state of charge between the module groups.
(12) In addition to one or more of the features described herein, the processor is further configured to change the mode of operation of the switch array.
(13) In addition to one or more of the features described herein, a module group includes a plurality of battery modules, each battery module of the module group connected to the respective switch via a unidirectional direct current (DC/DC) converter.
(14) In addition to one or more of the features described herein, the processor is further configured to cycle through the mode by performing a cyclic permutation of the configurations of the switch array.
(15) In addition to one or more of the features described herein, the respective switch is one of a single switch and a switch pair including a first switch for controlling the connection to the first low voltage bus and a second switch for controlling the connection to the second low voltage bus.
(16) In addition to one or more of the features described herein, the plurality of module groups includes at least three module groups.
(17) In yet another exemplary embodiment, a vehicle is disclosed. The vehicle includes a plurality of module groups, a switch array, and a processor. The switch array includes a plurality of switches, each switch coupled to a module group from the plurality of module groups and configured to be in one of a first state that connects the module group to a first low voltage bus, a second state that connects the module group to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus. The processor is configured to place the switch array in a configuration with at least one switch in one

of the first state and the second state, wherein the configuration defines a first phase of a mode of operation of the switch array and cycle through the mode to balance a state of charge between the plurality of module groups.
(18) In addition to one or more of the features described herein, the processor is further configured to adjust a duration of a phase to phase of the mode to passively balance the state of charge between the module groups.
(19) In addition to one or more of the features described herein, the processor is further configured to change the mode of operation of the switch array.
(20) In addition to one or more of the features described herein, a module group includes a plurality of battery modules, each battery module of the module group connected to the respective switch via a unidirectional direct current (DC/DC) converter.
(21) In addition to one or more of the features described herein, the processor is further configured to cycle through the mode by performing a cyclic permutation of the configurations of the switch array.
(22) In addition to one or more of the features described herein, the respective switch is one of a single switch and a switch pair including a first switch for controlling the connection to the first low voltage bus and a second switch for controlling the connection to the second low voltage bus.
(23) The above features and advantages, and other features and advantages of the disclosure are readily apparent from the following detailed description when taken in connection with the accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) Other features, advantages and details appear, by way of example only, in the following detailed description, the detailed description referring to the drawings in which:
(2) FIG. **1** shows a vehicle in accordance with an exemplary embodiment;
(3) FIG. **2** shows a circuit diagram for an electrical system of the vehicle, in an illustrative embodiment;
(4) FIG. **3** shows a high-level schematic diagram of a power circuit of the electrical system;
(5) FIG. **4** depicts a cycle through phases of a P.sub.1P.sub.1P.sub.2 mode, for illustrative purposes;
(6) FIG. **5** depicts a cycle through phases of a P.sub.1P.sub.2X mode, for illustrative purposes;
(7) FIG. **6** is a graph of state of charge against time;
(8) FIG. **7** is a graph of phase duration over time;
(9) FIG. **8** is graph of mode number over time; and
(10) FIG. **9** is graph of bus current over time.
DETAILED DESCRIPTION
(11) The following description is merely exemplary in nature and is not intended to limit the present disclosure, its application or uses. It should be understood that throughout the drawings, corresponding reference numerals indicate like or corresponding parts and features.
(12) In accordance with an exemplary embodiment, FIG. **1** shows an embodiment of a vehicle **10**, which includes a vehicle body **12** defining, at least in part, an occupant compartment **14**. The vehicle body **12** also supports various vehicle subsystems including a propulsion system **16**, and other subsystems to support functions of the propulsion system **16** and other vehicle components, such as a braking subsystem, a suspension system, a steering subsystem, and others.
(13) The vehicle **10** may be an electrically powered vehicle (EV), a hybrid vehicle or any other vehicle. In an embodiment, the vehicle **10** is an electric vehicle that includes multiple motors and/or drive systems. The vehicle **10** can be a car, a truck, a van, a bus, a motorcycle, or other type of automobile. Any number of drive units may be included, such as one or more drive units for

applying torque to front wheels (not shown) and/or to rear wheels (not shown). The drive units are controllable to operate the vehicle **10** in various operating modes, such as a normal mode, a high-performance mode (in which additional torque is applied), all-wheel drive ("AWD"), front-wheel drive ("FWD"), rear-wheel drive ("RWD") and others.

(14) For example, the propulsion system **16** is a multi-drive system that includes a front drive unit **20** for driving front wheels, and rear drive units for driving rear wheels. The front drive unit **20** includes a front electric motor **22** and a front inverter **24** (e.g., front power inverter module or FPIM), as well as other components such as a cooling system. A left rear drive unit **30**L includes a left rear electric motor **32**L and a left rear inverter **34**L. A right rear drive unit **30**R includes a right rear electric motor **32**R and a right rear inverter **34**R. The front inverter **24**, left rear inverter **34**L and right rear inverter **34**R (e.g., power inverter units or PIMs) each convert direct current (DC) power from a high voltage (HV) battery system **40** to poly-phase (e.g., two-phase, three-phase, six-phase, etc.) alternating current (AC) power to drive the front electric motor **22** the left rear electric motor **32**L and the right rear electric motor **32**R.

(15) As shown in FIG. **1**, the drive systems feature separate electric motors. However, embodiments are not so limited. For example, instead of separate motors, multiple drives can be provided by a single machine that has multiple sets of windings that are physically independent.

(16) As also shown in FIG. **1**, the drive systems are configured such that the front electric motor **22** drives the front wheels (not shown), and the left rear electric motor **32**L and right rear electric motor **32**R drive the rear wheels (not shown). However, embodiments are not so limited, as there may be any number of drive systems and/or motors at various locations (e.g., a motor driving each wheel, twin motors per axle, etc.). In addition, embodiments are not limited to a dual drive system, as embodiments can be used with a vehicle having any number of motors and/or power inverters.

(17) In the propulsion system **16**, the front drive unit **20**, left rear drive unit **30**L and right rear drive unit **30**R are electrically connected to the battery system **40**. The battery system **40** may also be electrically connected to other electrical components (also referred to as "electrical loads"), such as vehicle electronics (e.g., via an auxiliary power module or APM **42**), heaters, cooling systems and others. The battery system **40** may be configured as a rechargeable energy storage system (RESS).

(18) In an embodiment, the battery system **40** includes a plurality of separate battery assemblies, in which each battery assembly can be independently charged and can be used to independently supply power to a drive system or systems. For example, the battery system **40** includes a first battery assembly such as a first battery pack **44** connected to the front inverter **24**, and a second battery pack **46**. The first battery pack **44** includes a plurality of battery modules **48**, and the second battery pack **46** includes a plurality of battery modules **50**. Each battery module **48**, **50** includes a number of individual cells (not shown).

(19) Each of the front electric motor **22** and the left rear electric motor **32**L and right rear electric motor **32**R is a three-phase motor having three phase motor windings. However, embodiments described herein are not so limited. For example, the motors may be any poly-phase machines supplied by poly-phase inverters, and the drive units can be realized using a single machine having independent sets of windings.

(20) The battery system **40** and/or the propulsion system **16** includes a switching system having various switching devices for controlling operation of the first battery pack **44** and second battery pack **46**, and selectively connecting the first battery pack **44** and second battery pack **46** to the front drive unit **20**, left rear drive unit **30**L and right rear drive unit **30**R. The switching devices may also be operated to selectively connect the first battery pack **44** and the second battery pack **46** to a charging system. The charging system can be used to charge the first battery pack **44** and the second battery pack **46**, and/or to supply power from the first battery pack **44** and/or the second battery pack **46** to charge another energy storage system (e.g., vehicle-to-vehicle (V2V) and/or vehicle-to-everything (V2X) charging). The charging system includes one or more charging modules. For example, a first onboard charging module (OBCM) **52** is electrically connected to a

charge port **54** for charging to and from an AC system or device, such as a utility AC power supply. A second OBCM **53** may be included for DC charging (e.g., DC fast charging or DCFC).

(21) In an embodiment, the switching system includes a first switching device **60** that selectively connects to the first battery pack **44** to the front inverter **24**, left rear inverter **34**L and right rear inverter **34**R, and a second switching device **62** that selectively connects the second battery pack **46** to the front inverter **24**, left rear inverter **34**L and right rear inverter **34**R. The switching system also includes a third switching device **64** (also referred to as a "battery switching device") for selectively connecting the first battery pack **44** to the second battery pack **46** in series.

(22) Any of various controllers can be used to control functions of the electrical system of the vehicle, including the battery system **40**, the switching system the drive units, etc. A controller **65** includes any suitable processing device or unit and may use an existing controller such as a drive system controller, an RESS controller, and/or controllers in the drive system. For example, a controller **65** may be included for controlling switching and drive control operations as discussed herein.

(23) The controller **65** may include processing circuitry that may include an application specific integrated circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group) and memory that executes one or more software or firmware programs, a combinational logic circuit, and/or other suitable components that provide the described functionality. The controller **65** may include a non-transitory computer-readable medium that stores instructions which, when processed by one or more processors of the controller **65**, implement a method of balancing charge across various battery modules of the vehicle during operation of low voltage loads, according to one or more embodiments detailed herein.

(24) The vehicle **10** also includes a computer system **55** that includes one or more processing devices **56** and a user interface **58**. The computer system **55** may communicate with the charging system controller, for example, to provide commands thereto in response to a user input. The various processing devices, modules and units may communicate with one another via a communication device or system, such as a controller area network (CAN) or transmission control protocol (TCP) bus.

(25) As illustrated herein, the vehicle **10** is an electric vehicle. In an alternative embodiment, the vehicle **10** can be an internal combustion engine vehicle fueled by gasoline, diesel, etc., a hybrid vehicle partially or wholly powered by electrical power, etc.

(26) As described herein, a vehicle can include one or more electrical loads that are powered by one or more batteries. Exemplary loads include, but are not limited to motors, lights, infotainment equipment, electronic control units, climate control systems, etc. The electrical loads can be high voltage load or low voltage loads, and the battery system **40** (e.g., one or more of the first battery pack **44** and the second battery pack **46**) can provide both high voltage to the high voltage loads and low voltage to the low voltage loads. According to one or more embodiments described herein, a high voltage can refer to, but is not limited to, 100 volts, 250 volts, 400 volts, 500 volts, 650 volts, 800 volts, 1000 volts, etc. The low voltage can refer to, but is not limited to, 12 V, 48V etc. To support these low voltage loads, the vehicle **10** can include at least one DC/DC converter to convert DC electric power from the higher voltage to the lower voltage, as disclosed herein.

(27) FIG. **2** shows a circuit diagram for an electrical system **200** of the vehicle **10**, in an illustrative embodiment. The electrical system **200** includes a grid system **202**, a power circuit **204**, a switch array **206**, and a control circuit **208**. The grid system **202** includes various low voltage loads of the vehicle **10**. The power circuit **204** includes various electrical elements for providing power to the low voltage loads. The switch array **206** include switches that control connections between the electrical elements of the power circuit **204** and the low voltage loads of the grid system **202**. The switch array **206** also can be used to balance charge between the electrical elements of the power circuit **204**, as disclosed herein. The control circuit **208** can be a processor operating one or more algorithms for controlling operation of the electrical elements of the switch array **206**.

(28) For illustrative purposes, the grid system **202** includes a first low voltage grid **210** and a second low voltage grid **212**. In other embodiments, more than two voltage grids can be included in the grid system **202**. The first low voltage grid **210** includes a first low voltage load **214** and a first load regulator **216**. The second low voltage grid **212** includes a second low voltage load **218** and a second load regulator **220**.
(29) The power circuit **204** includes a battery pack **222** and a DC converter array **224**. The battery pack **222** includes a plurality of module groups **226***a*, **226***b*, **226***c*. Each module group **226***a*, **226***b*, **226***c* includes a plurality of battery modules. For illustrative purposes, a first module group **226***a*, a second module group **226***b*, and a third module group **226***c* are shown. However, it is understood that any plural number of module groups can be included in the battery pack **222** in various embodiments. The module groups **226***a*, **226***b*, **226***c* are wired in series with each other along a high voltage bus **228**. Each module group **226***a*, **226***b*, **226***c* includes an associated module balancing controller **230***a*, **230***b*, **230***c*. Each module balancing controller (e.g., module balancing controller **230***a*) is used to balance state of charge (SOC) between the battery modules of the associated module group (e.g., module group **226***a*). The module balancing controllers **230***a*, **230***b*, **230***c* can receive feedback signals indicative of a first load regulator current (i.sup.reg.sub.LV1), a second load regulator current (i.sup.reg.sub.LV2) and an estimation of state of charge.
(30) The DC converter array **224** includes DC converter groups **232***a*, **232***b*, **232***c*. Each DC converter groups is associated with a respective module group. (e.g., first DC converter group **232***a* is associated with first module group **226***a*). Each DC converter group includes a plurality of DC/DC converters (such as DC converters **234***a*, **234***b*, **234***c*), wherein a primary end of each DC/DC converter is coupled to a respective module of the associated module group (e.g., module group **226***a*). Each DC/DC converter is a unidirectional converter.
(31) The switch array **206** includes a plurality of switch groups **236***a*, **236***b*, **236***c*. Each switch group is associated with a respective DC converter group. For example, switch group **236***a* is connected to a secondary side of the DC converter group **232***a*. A switch group can include multiple switches. For example, the first switch group **236***a* includes a first switch **238***a* (U.sub.1) and a second switch **238***b* (Z.sub.1). The first switch U.sub.1 controls a connection between the first DC converter group **226***a* and the first low voltage grid **210**. The second switch Z.sub.1 controls a connection between the first DC converter group **226***a* and the second low voltage grid **212**.
(32) The first switch U.sub.1 and the second switch Z.sub.1 can be placed in several configurations. In a first configuration, the first switch U.sub.1 is in an ON state and the second switch Z.sub.1 is in an OFF state, thereby connecting the first module group to the first low voltage grid **210**, with the second low voltage grid **212** disconnected from the first module group. In a second configuration, the first switch U.sub.1 is in an OFF state and the second switch Z.sub.1 is in an ON state, thereby connecting the first module group **226***a* to the second low voltage grid **212**, with the first low voltage grid **210** disconnected from the first module group. In a third configuration, the first switch U.sub.1 and the second switch Z are both in an OFF state, thereby disconnecting the first module group **226***a* from both the first low voltage grid **210** and the second low voltage grid **212**. The first switch U.sub.1 and the second switch Z.sub.1 cannot both be in an ON state when a balancing controller algorithm disclosed herein is enabled. Similar configurations are available for the switches U.sub.2 and Z.sub.2 of the second switch group **236***b* and switches U.sub.3 and Z.sub.3 of the third switch group **236***c*.
(33) The control circuit **208** operates a state of charge balancing control algorithm **240**, a state of charge estimation algorithm **242**, and a mode determination algorithm **244**. The state of charge balancing algorithm-**240** controls configuration of the switches of the switch array **206** (i.e., switches of the first switch group **236***a*, second switch group **236***b* and third switch group **236***c*).
(34) The state of charge estimation algorithm **242** receives data from sensors that can measure current, voltage and temperature at the module groups or at individual battery modules within a

module group. The state of charge estimation algorithm **242** can supply state of charge values to a module balancing controller of a selected module group (i.e., module balancing controller **230***a* of the first module group **226***a*) which performs actions to balance charge between the battery modules of the selected module group. The state of charge estimation algorithm **242** can also supply state of charge values to the charge balancing control algorithm **240**, which controls the configuration of the switch array **206** based on the state of charge values.
(35) The mode determination algorithm **240** receives input about the demands of the low voltage loads and outputs a mode of operation and a mode duration that can be used at the charge balancing algorithm **240** to control the configuration of the switch array **206**. Further discussion of the mode of operation and mode duration is described herein with respect to FIG. **3** and Table 1.
(36) FIG. **3** shows a high-level schematic diagram **300** of the power circuit **204** of FIG. **2**. The high-level schematic diagram **300** shows the module groups **226***a*, **226***b*, **226***c*, associated DC converter groups **232***a*, **232***b*, **232***c*, and associated switches **302***a*, **302***b*, **302***c* (equivalent representations of the switch groups **236***a*, **236***b*, **236***c* of FIG. **2**). Four battery modules **304***a*, **304***b*, **304***c*, **304***d* of the first module group **226***a* are shown for illustrative purposes. In various embodiments, any number of modules can be included in a module group. The switch groups **236***a*, **236***b*, **236***c* are each depicted as a single switch having the ability either to connect to a first low voltage bus **306** associated with the first low voltage grid **210**, to connect to a second low voltage bus **308** associated with the second low voltage grid **212**, or to be in a neutral or OFF state. For purpose of illustration, the first switch **302***a* is depicted as being connected to the first low voltage bus **306** and is therefore in a state referred to as a P.sub.1 state. The second switch **302***b* is depicted as being connected to the second low voltage bus **308** and is therefore in a state referred to as a P.sub.2 state. The third switch **302***c* is depicted as being disconnected from both the first low voltage bus **306** and the second low voltage bus **308** and is therefore in a state referred to as an X state. As a unit, the array including the first switch **302***a*, second switch **302***b* and third switch **302***c* is referred to as operating in a P.sub.1P.sub.2X mode.
(37) A switch mode includes various phases that are performed in sequence. Each phase includes the switches in a particular configuration (e.g., P.sub.1P.sub.2X). Each phase is related to a previous phase by a cyclic permutation of the states of the switches. For example, the configuration of switches as shown in FIG. **3** (i.e., P.sub.1P.sub.2X) defines a first phase of the mode. A second phase thus includes the switches in an XP.sub.1P.sub.2 configuration and a third phase includes the switches in a P.sub.2XP.sub.1 configuration. Operation of the mode includes cycling from the first phase to the second phase to the third phase and then back to the first phase. The duration of the mode and the duration of the phases can be controlled by the mode determination algorithm **244**.
(38) Table 1 shows various modes for the switches and their associated phases. The state of charge balancing control algorithm **240** controls the configuration of the switch array **206** and adjusts durations of each phase to balance the states of charge of the module groups.
(39) TABLE-US-00001 TABLE 1 Mode # Phase 1 Phase 2 Phase 3 1 XXX XXX XXX 2 XXP.sub.1 P.sub.1XX XP.sub.1X 3 XXP.sub.2 P.sub.2XX XP.sub.2X 4 XP.sub.1P.sub.1 P.sub.1XP.sub.1 P.sub.1P.sub.1X 5 XP.sub.2P.sub.2 P.sub.2XP.sub.2 P.sub.2P.sub.2X 6 XP.sub.1P.sub.2 P.sub.2XP.sub.1 P.sub.1P.sub.2X 7 P.sub.1P.sub.1P.sub.2 P.sub.2P.sub.1P.sub.1 P.sub.1P.sub.2P.sub.1 8 P.sub.1P.sub.2P.sub.2 P.sub.2P.sub.1P.sub.2 P.sub.2P.sub.2P.sub.1 9 P.sub.1P.sub.1P.sub.1 P.sub.1P.sub.1P.sub.1 P.sub.1P.sub.1P.sub.1 10 P.sub.2P.sub.2P.sub.2 P.sub.2P.sub.2P.sub.2 P.sub.2P.sub.2P.sub.2
(40) FIG. **4** depicts a cycle **400** through phases of a P.sub.1P.sub.1P.sub.2 mode, for illustrative purposes. The cycle **400** includes a first phase **402** (P.sub.1P.sub.1P.sub.2), a second phase **404** (P.sub.2P.sub.1P.sub.1) and a third phase **406** (P.sub.1P.sub.2P.sub.1). In the first phase **402**, both the first module group **226***a* and the second module group **226***b* are connected to the same bus (i.e., the first low voltage bus **306**), thereby allowing a charge transfer and thus charge balancing between the first module group and the second module group. Similarly, in the second phase, both

the second module group **226***b* and the third module group **226***c* are connected to the same bus (i.e., the first low voltage bus **306**), thereby allowing a charge transfer and thus charge balancing between the second module group and the third module group. In the third phase, both the third module group **226***c* and the first module group **226***a* are connected to the same bus (i.e., the first low voltage bus **306**), thereby allowing a charge transfer and thus charge balancing between the third module group and the first module group. Cycling through the P.sub.1P.sub.1P.sub.2 mode adjusts a power distribution to the first low voltage bus **306** and the second low voltage bus **308**.
(41) FIG. **5** depicts a cycle **500** through phases of a P.sub.1P.sub.2X mode, for illustrative purposes. The cycle **500** includes a first phase **502** (P.sub.1P.sub.2X), a second phase **504** (XP.sub.1P.sub.2) and a third phase **506** (P.sub.2XP.sub.1). In the first phase **502**, the first module group **226***a* is connected to the first low voltage bus **306** and the second module group **226***b* is connected to the second low voltage bus **308**. The third module group **226***c* is not connected to either bus. In the second phase, the second module group **226***b* is connected to the first low voltage bus **306** and the third module group **226***c* is connected to the second low voltage bus **308**. The first module group **226***a* is not connected to either bus. In the third phase, the third module group **226***c* is connected to the first low voltage bus **306** and the first module group **226***a* is connected to the second low voltage bus **308**. The second module group **226***b* is not connected to either bus. Cycling through the P.sub.1P.sub.2X mode provides equal power to the first low voltage bus **306** and the second low voltage bus **308**.
(42) FIG. **6** is a graph **600** of state of charge against time. Time is shown along the abscissa in seconds and SOC is shown along the ordinate axis, wherein the value of SOC=1 refers to a fully charged module and SOC=0 is a fully discharged module. The SOCs of the modules are initially balanced (i.e., same SOC at time t=5500 seconds). The modules are operated up until time t=0 with equal phase duration. Over time, the SOCs of the modules diverge, as shown by the divergence between first SOC **602** of the first module group **226***a*, second SOC **604** of the second module group **226***b*, and third SOC **606** of the third module group **226***c*. At time t=0, the change balancing operation disclosed herein is implemented. The first SOC **602**, second SOC **604** and third SOC **606** soon converge to a same value (i.e., within about 100 seconds).
(43) FIG. **7** is a graph **700** of phase duration over time. Time is shown along the abscissa in seconds and phase duration is shown as a normalized value along the ordinate axis. From t=−5500 seconds to t=0 seconds, the durations of the phases are the same value (e.g., about 0.4). At time t=0, the duration of the phases are changed to cause balancing between modules, as shown by first phase duration **702**, second phase duration **704** and third phase duration **706**.
(44) FIG. **8** is graph **800** of mode number over time. Time is shown along the abscissa in seconds and mode number (see column 1 of Table 1) is shown along the ordinate axis. Curve **802** shows the mode number at a given time and indicates the shifting between modes as appropriate.
(45) FIG. **9** is graph **900** of bus current over time. Time is shown along the abscissa in seconds and current is shown along the ordinate axis. Curve **902** shows the current along the first low voltage bus **306** (P**1**) and curve **904** shows the current along the second low voltage bus **308** (P**2**).
(46) The terms “a” and “an” do not denote a limitation of quantity, but rather denote the presence of at least one of the referenced item. The term “or” means “and/or” unless clearly indicated otherwise by context. Reference throughout the specification to “an aspect”, means that a particular element (e.g., feature, structure, step, or characteristic) described in connection with the aspect is included in at least one aspect described herein, and may or may not be present in other aspects. In addition, it is to be understood that the described elements may be combined in any suitable manner in the various aspects.
(47) When an element such as a layer, film, region, or substrate is referred to as being “on” another element, it can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being “directly on” another element, there are no intervening elements present.

(48) Unless specified to the contrary herein, all test standards are the most recent standard in effect as of the filing date of this application, or, if priority is claimed, the filing date of the earliest priority application in which the test standard appears.
(49) Unless defined otherwise, technical and scientific terms used herein have the same meaning as is commonly understood by one of skill in the art to which this disclosure belongs.
(50) While the above disclosure has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from its scope. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the disclosure without departing from the essential scope thereof. Therefore, it is intended that the present disclosure not be limited to the particular embodiments disclosed, but will include all embodiments falling within the scope thereof.

Claims

1. A method of balancing a state of charge between module groups of a battery pack of a vehicle, comprising: connecting the module groups in series along a high voltage bus; for each module group, connecting the module group to a respective switch of a switch array, wherein the respective switch is configured to be in one of a first state in which the module group is connected to a first low voltage bus, a second state in which the module group is connected to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus; placing the switch array for each module group in a configuration with at least one switch in one of the first state and the second state, wherein the configuration defines a first phase of a mode of operation of the switch array; and cycling through the phase of the mode of operation to balance the state of charge between the module groups.
2. The method of claim 1 further comprising adjusting duration of a phase of the mode to passively balance the state of charge between the module groups.
3. The method of claim 1, further comprising changing the mode of operation of the switch array.
4. The method of claim 1, wherein a module group includes a plurality of battery modules, further comprising connecting each battery module of the module group to the respective switch via a unidirectional direct current (DC/DC) converter.
5. The method of claim 1, wherein cycling through the mode further comprising performing a cyclic permutation of the configurations of the switch array.
6. The method of claim 1, wherein the respective switch is one of: (i) a single switch; and (ii) a switch pair including a first switch for controlling the connection to the first low voltage bus and a second switch for controlling the connection to the second low voltage bus.
7. The method of claim 1, wherein the module groups include at least three module groups.
8. An electrical system for a vehicle, comprising: a high voltage bus; a plurality of module groups connected in series along the high voltage bus; a switch array including a plurality of switches, each switch coupled to a module group from the plurality of module groups and configured to be in one of a first state that connects the module group to a first low voltage bus, a second state that connects the module group to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus; and a processor configured to: place the switch array for each module group in a configuration with at least one switch in one of the first state and the second state, wherein the configuration defines a first phase of a mode of operation of the switch array; and cycle through the phases of the mode of operation to balance a state of charge between the plurality of module groups.
9. The electrical system of claim 8, wherein the processor is further configured to adjust a duration of a phase of the mode to passively balance the state of charge between the module groups.
10. The electrical system of claim 8, wherein the processor is further configured to change the

mode of operation of the switch array.

11. The electrical system of claim 8, wherein a module group includes a plurality of battery modules, each battery module of the module group connected to the respective switch via a unidirectional direct current (DC/DC) converter.

12. The electrical system of claim 8, wherein the processor is further configured to cycle through the mode by performing a cyclic permutation of the configurations of the switch array.

13. The electrical system of claim 8, wherein the respective switch is one of: (i) a single switch; and (ii) a switch pair including a first switch for controlling the connection to the first low voltage bus and a second switch for controlling the connection to the second low voltage bus.

14. The electrical system of claim 8, wherein the plurality of module groups includes at least three module groups.

15. A vehicle, comprising: a high voltage bus; a plurality of module groups connected in series along the high voltage bus; a switch array including a plurality of switches, each switch coupled to a module group from the plurality of module groups and configured to be in one of a first state that connects the module group to a first low voltage bus, a second state that connects the module group to a second low voltage bus, and a third state in which the module group is disconnected from both the first low voltage bus and the second low voltage bus; and a processor configured to: place the switch array for each module group in a configuration with at least one switch in one of the first state and the second state, wherein the configuration defines a first phase of a mode of operation of the switch array; and cycle through the phases of the mode of operation to balance a state of charge between the plurality of module groups.

16. The vehicle of claim 15, wherein the processor is further configured to adjust a duration of a phase to phase of the mode to passively balance the state of charge between the module groups.

17. The vehicle of claim 15, wherein the processor is further configured to change the mode of operation of the switch array.

18. The vehicle of claim 15, wherein a module group includes a plurality of battery modules, each battery module of the module group connected to the respective switch via a unidirectional direct current (DC/DC) converter.

19. The vehicle of claim 15, wherein the processor is further configured to cycle through the mode by performing a cyclic permutation of the configurations of the switch array.

20. The vehicle of claim 15, wherein the respective switch is one of: (i) a single switch; and (ii) a switch pair including a first switch for controlling the connection to the first low voltage bus and a second switch for controlling the connection to the second low voltage bus.