Title: BATTERY BALANCING SYSTEM AND METHOD

Abstract: Provided is a battery balancing system arranged to be electrically connected to an external load and an auxiliary load, the system comprising a plurality of cell units, each being arranged to be connected in series with: i) the external load, or ii) the auxiliary load. The system also comprises a controller arranged to determine the state of charge of each of the cell units, and an electrical connection mechanism associated with each cell unit and arranged to be controlled by the controller based on the determined state of charge of the associated cell unit, wherein during a discharge cycle of the cell units each electrical connection mechanism is arranged to: i) electrically connect its associated cell unit to the external load in series with other cell units, ii) electrically connect its associated cell unit to the auxiliary load, alone or in series with other cell units, or iii) electrically disconnect its associated cell unit from the external load and the auxiliary load, in order to control the state of charge of each cell unit. Also provided is a battery balancing system for a charge cycle and battery balancing methods.
BATTERY BALANCING SYSTEM AND METHOD

Field of the Invention

The present invention is generally related to a battery balancing system and particularly, although not exclusively, related to an active battery balancing system.

Background to the Invention

Hybrid and pure battery electric drivetrains can be a low-emission, cost-neutral and performance-increasing alternative to petrol-engine-based and diesel-engine-based drivetrains. Typically, there are three components that are common to electrified drivetrains: i) an electric motor, ii) power electronics that control the motor, and iii) a battery system that provides energy to the motor. The battery system may be the largest, heaviest, and most complex and expensive component in an electric vehicle. Typically, modern electric vehicles use lithium-ion (Li-ion) cells because of their large energy capacity per unit weight, moderate cost per unit energy storage and relatively high technological maturity. However, overcharging or overdischarging Li-ion cells can have risks including excessive heating, cell degradation, and burning. Therefore, close monitoring and control of the cells may be required for safe operation.

Electric vehicle battery systems can contain a large number of individual Li-ion cells (tens to thousands). Efficient transmission of electrical energy from the battery to the motor requires a high voltage, such as 300 V to 400 V, and individual cells can be chemically limited to a voltage output of approximately 2 V to 4 V; many series-connected cells may be required to provide a suitable voltage output. Series-connected cells share charging and discharging currents but do not necessarily have the same voltages.

Each cell has an inherent energy capacity and state of charge (SOC) at any given moment, and each cell’s SOC can be different to the SOCs of other cells. In practice, manufacturing tolerances mean that cells can begin their working life with certain manufacturing variations and therefore a certain amount of unbalance with regards to SOC. As the cells progress through their life, unequal ageing means that cell unbalance may continue to grow. The cells may be charged by applying a high voltage across the complete string of series-connected cells. When charging an unbalanced string of cells, if cells are charged until the charging voltage is equal to the number of cells in the string multiplied by the maximum voltage rating of each cell, cells with an SOC lower than average are not yet fully charged, while cells with an SOC higher than average are overcharged.

Charging can be stopped earlier when the first cell voltage crosses its maximum voltage boundary, but this means many cells will not be fully charged and therefore the energy
capacity of the string will reduce. Analogously, discharging unbalanced strings leads low-SOC cells to hit the minimum boundary while high-SOC cells still have stored energy remaining. Cells can age particularly quickly near the very top and bottom of their operating region. Cycle charging unbalanced strings and stopping whenever a cell reaches the maximum or minimum boundary can cause high-SOC cells to age quickly due to operating in their upper SOC region, and low-SOC cells to age quickly due to operating in their lower SOC region.

Summary of the Invention

In a first broad aspect the invention provides a battery balancing system arranged to be electrically connected to an external load and an auxiliary load, the system comprising:

- a plurality of cell units, each being arranged to be connected in series with: i) the external load, or ii) the auxiliary load,
- a controller arranged to determine the state of charge of each of the cell units, and
- an electrical connection mechanism associated with each cell unit and arranged to be controlled by the controller based on the determined state of charge of the associated cell unit, wherein during a discharge cycle of the cell units each electrical connection mechanism is arranged to: i) electrically connect its associated cell unit to the external load in series with other cell units, ii) electrically connect its associated cell unit to the auxiliary load, alone or in series with other cell units, or iii) electrically disconnect its associated cell unit from the external load and the auxiliary load, in order to control the state of charge of each cell unit.

In an embodiment, one or more of the electrical connection mechanisms is a DC-to-DC converter.

In an embodiment, one or more of the electrical connection mechanisms is a plurality of switches.

In an embodiment, each electrical connection mechanism comprises a main power circuit bypass switch arranged to operate to bypass its associated cell unit from a main power circuit upon determination that the cell unit is to be switched into an auxiliary power circuit.

In an embodiment, each electrical connection mechanism comprises a cell line switch arranged to: i) close to connect in series adjacent cell units or the first cell unit and the external load upon determination that such adjacent cell units or the first cell unit and the external load are to be switched into the same circuit, and ii) open to disconnect adjacent cell units or the first cell unit and the external load upon determination that such adjacent cell units or the first cell unit and the external load are to be switched into different circuits.
In an embodiment, each electrical connection mechanism comprises a first main power circuit switch and a second main power circuit switch arranged to switch their associated cell unit into a main power circuit.

In an embodiment, each electrical connection mechanism comprises an auxiliary power circuit bypass switch arranged to operate to bypass its associated cell unit from an auxiliary power circuit upon determination that the cell unit is to be switched into a main power circuit.

In an embodiment, each electrical connection mechanism comprises a positive auxiliary power circuit switch and a negative auxiliary power circuit switch arranged to switch their associated cell unit into an auxiliary power circuit.

In an embodiment, the battery balancing system comprises a plurality of auxiliary power rails arranged such that one or more cell units can be connected in series with the auxiliary load via the plurality of auxiliary rails.

In an embodiment, the battery balancing system comprises a master switch arranged to temporarily disconnect the external load, the auxiliary load or both from the cell units while the electrical connection mechanisms operate.

In a second broad aspect the invention provides a battery balancing system arranged to be electrically connected to a power source, the system comprising:

- a plurality of cell units, each being arranged to be connected in series with the power source,
- a controller arranged to determine the state of charge of each of the cell units, and an electrical connection mechanism associated with each cell unit and arranged to be controlled by the controller based on the determined state of charge of the associated cell unit, wherein during a charge cycle of the cell units each electrical connection mechanism is arranged to: i) electrically connect its associated cell unit to the power source in series with other cell units, or ii) electrically disconnect its associated cell unit from the power source, in order to control the state of charge of each cell unit.

In an embodiment, one or more of the electrical connection mechanisms is a DC-to-DC converter.

In an embodiment, one or more of the electrical connection mechanisms is a plurality of switches.
In an embodiment, each electrical connection mechanism comprises a main power circuit bypass switch arranged to operate to bypass its associated cell unit from a main power circuit upon determination that the cell unit is not to be switched into the main power circuit.

In an embodiment, each electrical connection mechanism comprises a cell line switch arranged to: i) close to connect in series adjacent cell units or the first cell unit and the power source upon determination that such adjacent cell units or the first cell unit and the power source are to be switched into the same circuit, and ii) open to disconnect adjacent cell units or the first cell unit and the power source upon determination that such adjacent cell units or the first cell unit and the power source are not to be switched into the same circuit.

In an embodiment, each electrical connection mechanism comprises a first main power circuit switch and a second main power circuit switch arranged to switch their associated cell unit into a main power circuit.

In an embodiment, the battery balancing system comprises a master switch arranged to temporarily disconnect the power source from the cell units while the electrical connection mechanisms operate.

In a third broad aspect the invention provides an electric vehicle comprising the battery balancing system according to either the first broad aspect or the second broad aspect.

In a fourth broad aspect, the invention provides a battery balancing method comprising:

- determining a state of charge for each cell unit of a plurality of cell units,
  - during a discharge cycle and based on the determined state of charge for each cell unit, controlling the electrical connection of each cell unit to: i) electrically connect it to an external load in series with other cell units, ii) electrically connect it to an auxiliary load, alone or in series with other cell units, or iii) electrically disconnect it from the external load and the auxiliary load, in order to control the state of charge of each cell unit.

In a fifth broad aspect the invention provides a battery balancing method comprising:

- determining a state of charge for each cell unit of a plurality of cell units,
  - during a charge cycle and based on the determined state of charge for each cell unit, controlling the electrical connection of each cell unit to: i) electrically connect it to a power source in series with other cell units, or ii) electrically disconnect it from the power source, in order to control the state of charge of each cell unit.
In a sixth broad aspect the invention provides computer program code which when executed implements the method of either the fourth broad aspect or the fifth broad aspect.

In a seventh broad aspect the invention provides a tangible readable memory comprising the computer program code of the sixth broad aspect.

**Brief Description of the Drawings**

In order that the invention may be more clearly ascertained, embodiments will now be described, by way of example, with reference to the accompanying drawing, in which:

Figure 1 is a circuit diagram of an embodiment of the invention comprising electrical connection mechanisms provided as a plurality of switches,

Figure 2 is an enlarged view of the portion of the circuit diagram of Figure 1 marked AA',

Figure 3a is the circuit diagram of Figure 1 showing three cells connected in series with an external load,

Figure 3b is the circuit diagram of Figure 1 showing one cell connected in series with an auxiliary load,

Figure 3c is the circuit diagram of Figure 1 showing the combination of the circuits of Figures 3a and 3b,

Figure 4 is a circuit diagram of another embodiment of the invention comprising a plurality of auxiliary rails, and

Figure 5 is a circuit diagram of another embodiment of the invention comprising electrical connection mechanisms provided as DC-to-DC converters.

**Detailed Description of Embodiments of the Invention**

The invention is generally related to a battery balancing system and method that may be used in an electric vehicle, such as a battery electric vehicle, hybrid electrical vehicle or plug-in hybrid electric vehicle, or similar applications. The battery balancing system comprises a controller and a plurality of battery cell units arranged to be connected in series. In some embodiments, each battery cell unit is an individual battery cell arranged to be connected in series with other individual battery cells. In other embodiments, each battery cell unit comprises a block of two or more cells connected in parallel and arranged to be connected in series with other blocks of parallel-connected cells. In some
embodiments, the plurality of battery cell units can comprise a combination of individual
battery cells and blocks of parallel-connected cells. In this specification and the claims that
follow, the terms "battery cell unit" or "cell unit" can refer to an individual battery cell or a
block of cells connected in parallel, and similar reasoning applies to variations of those
terms, such as plurals. Each cell unit has an associated electrical connection mechanism.
In one embodiment, the electrical connection mechanism comprises a plurality of switches,
as will be described in more detail below. In another embodiment, the electrical connection
mechanism comprises a converter, which is typically a DC-to-DC converter, as will be
described in more detail below.

The invention is generally arranged to facilitate power transfer: i) from the battery cell units
to an external load (such as an electric motor), during a discharge cycle, and ii) from a
power source (such as an electric vehicle charging station) to the battery cell units, during a
charge cycle. Typically the invention facilitates one of a charge or discharge cycle at any
given time, but not both at the same time. In particular, a main power circuit facilitates the
transfer of power between the cell units and the external load/power source. Concurrently,
an auxiliary power circuit may provide power to an auxiliary load.

Referring to Figure 1, in an embodiment, the battery balancing system 2 comprises a
plurality of battery cell units 4 arranged to be connected in series through a plurality of
electrical connection mechanisms, where each electrical connection mechanism comprises
a plurality of switches 6. It is noted that the figures illustrate embodiments where the
plurality of cell units 4 is a plurality of series-connected individual cells, but the invention
may comprise a series-connected plurality of blocks of two or more parallel-connected
cells, or a combination thereof. The cell units 4 may comprise lithium-ion battery cells or
any other suitable type of rechargeable battery cell. The switches 6 may be silicon-based
semiconductor switches such as silicon MOSFETS or IGBTs. The switches 6 may be wide
band-gap semiconductors that use materials such as silicon-carbide (SiC) or gallium
nitrate (GaN). The switches 6 may be electromechanical contactors such as starter
solenoids as found in cars. Typically, single-throw switches are used, but some
embodiments may include one or more semiconductor-based or electromechanical double-
throw switches. However, any suitable switch 6 or combination thereof may be used.

The battery balancing system 2 typically comprises a number of electrically conductive
pathways or conductors 8 arranged to facilitate the flow of electrical energy between the
components of the system 2. The battery balancing system 2 is arranged to be connected
to a power source (such as a charging station) or an external load 10 (such as an electric
motor) for respectively charging and discharging the cell units via the main power circuit.
The external load 10 and power source is typically connected to the battery balancing
system 2 and the main power circuit via suitable power electronics 11. The battery balancing system 2 is also arranged to be connected to an auxiliary load 12 via the auxiliary power circuit, where the auxiliary load 12 may comprise an electric vehicle's low-voltage power system or a subset of the components of the low-voltage power system, which may include lights, a sound system, a horn or any other suitable components. Suitable switches 6 may have an isolation voltage and current rating higher than the voltage and current rating of the external load 10 and power source, and minimal on resistance. The external load 10 may have an associated inverter if an AC input is required, the power source may have an associated rectifier if AC output is provided, and the auxiliary load 12 may have an associated regulator.

The battery balancing system comprises a controller (not shown) connected to and arranged to control the switches 6. The controller is typically a piece of hardware, such as a microcontroller, comprising readable memory arranged to store computer program code in the form of firmware or software defining control instructions in order to implement the method described below. However, any suitable controller may be used. Any suitable programming language may be used. The memory is typically non-volatile memory, such as flash memory or erasable programmable read only memory (EPROM), though any suitable memory type may be used. The controller may be part of the auxiliary load 12 and hence it may ultimately be powered by the battery balancing system.

The battery balancing system 2 may be used to provide power to an electric vehicle motor at, for example, 300 V to 400 V. (Such electric vehicle motors may have a power rating of, for example, 80 kWh to 310 kWh.) However, the battery balancing system 2 may be used to provide power to any suitable load at any suitable voltage and power rating. Conversely, the battery balancing system may be used to receive power from a power source at any suitable power rating, voltage and current. Typically, individual cells are limited, for example chemically, to an output voltage of 2 V to 4 V. This means that in some systems approximately one hundred cells are connected in series in order to provide a suitable load voltage.

The controller is arranged to detect or estimate the state of charge ("SOC") of each cell unit 4. For example, the controller may be arranged to read the voltage of a cell unit 4 and to compare that voltage with a representation of that cell unit's known discharge curve, which may be stored in memory. In this way, the controller can determine which cell units 4 are overcharged or undercharged, and act to appropriately switch such determined cell units into or out of appropriate circuits in order to balance the SOC of the cell units. For example, at a given moment during a discharge cycle in a system with one hundred cell units, ninety series-connected cell units may be used to power the external load 10, four
series-connected cell units 4 may be used to power the auxiliary load 12, and six redundant cell units may not be connected to any circuit. During such a battery system’s discharge cycle (such as when the electric vehicle is being driven), the controller may determine that one of the cell units 4 driving the external load 10 has a low SOC and in response switch that cell unit 4 out of the main power circuit and into the less power-intensive auxiliary power circuit, while switching a suitable cell unit 4 (for example, a high-SOC cell unit) out of the auxiliary power circuit. In this manner, the low-SOC cell unit 4 may now discharge more slowly than its external load 10 peers, in order that battery or cell unit 4 balancing can be achieved. Alternatively, the low-SOC cell unit may be disconnected from all circuits until it is determined to have an average SOC. However, the cell units 4 may be switched in any suitable manner to achieve SOC balancing.

Similarly, during a battery system’s charge cycle (such as when the electric vehicle is being charged), the controller may determine that one of the charging cell units 4 has a high SOC and in response switch that cell unit out of the main power circuit until it is determined to have an average SOC.

Referring to Figures 1 and 2, the battery balancing system 2 may comprise conductors 8 that act as: i) a cell line 8a comprising the cell units 4 and associated switches 6 such that each cell unit 4 can be connected in series with the external load 10, power source or auxiliary load 12, ii) a main power circuit bypass line 8b comprising switches 6 such that each cell unit 4 can be switched out of (i.e. bypassed) the main power circuit when necessary, iii) an auxiliary power circuit 12 bypass line 8c comprising switches 6 such that each cell unit 4 can be switched out of (i.e. bypassed) the auxiliary power circuit when necessary, iv) a main power circuit negative rail 8d, and v) an auxiliary power circuit positive rail 8e. The functions of these conductors 8 are discussed further below.

In this specification, the first cell unit is denoted 4.1, the second cell unit is denoted 4.2, and so on. Associated switches follow a similar format. For example, a particular switch associated with the second cell unit 4.2 is denoted 6.2.1, a second particular switch associated with the second cell unit 4.2 is denoted 6.2.2, and so on.

A master switch (not shown) may be provided that is arranged to temporarily disconnect the external load 10, auxiliary load 12 or both, or the power source from the main power circuit or auxiliary power circuit while other switches 6 operate. A master switch operating in this manner may lower the switching currents and voltages applied to the cell units 4 during switching, which may increase lifespans of the cell units 4 and provide for faster switching times. These advantages may be particularly prevalent in embodiments that use mechanical switches, but advantages may also be provided in embodiments that use semi-
conductor based switches or other switches. The master switch may be provided, for example, at node 20.

Embodiments including a master switch may also include one or more capacitors associated with, and arranged to provide stored energy to, the external load 10 / power source. The one or more capacitors typically provide stored energy to the external load 10 / power source during the temporary disconnection from the main power circuit when the master switch is switched off. Similarly, one or more capacitors may be associated with, and arranged to provide stored energy to, the auxiliary load 12 during the temporary disconnection from the auxiliary power circuit when the master switch is switched off. Referring to Figure 2, the cell units 4, controller, switches 6 and conductors 8 are arranged in the battery balancing system 2 such that each cell unit 4 (such as individual cells or blocks of parallel-connected cells) can be: i) switched into the main power circuit and out of the auxiliary power circuit, ii) switched into the auxiliary power circuit and out of the main power circuit, and iii) switched out of both the main power and auxiliary power circuits. This means that during operation, the battery balancing system 2 typically comprises two complete circuits, namely the main power circuit comprising: i) the external load 10 or power source and one or more series-connected cell units 4, and ii) the auxiliary power circuit comprising the auxiliary load 12 and one or more series-connected cell units; the number of series-connected cell units 4 switched into the external main power circuit generally exceeds the number of series-connected cell units 4 switched into the auxiliary power circuit.

In an embodiment, each cell unit 4 has a number of associated switches 6. For example, a cell unit 4.2 has an associated main power circuit bypass switch 6.2.1 that is arranged to: i) open to assist in switching the cell unit 4.2 into the main power circuit and out of the main power circuit bypass line 8b, and ii) close to assist in switching the cell unit 4.2 into the main power circuit bypass line 8b and out of the main power circuit.

In this embodiment, the cell unit 4.2 also has an associated auxiliary power circuit bypass switch 6.2.2 that is arranged to: i) open to assist in switching the cell unit 4.2 into the auxiliary power circuit and out of the auxiliary power circuit bypass line 8c, and ii) close to assist in switching the cell unit 4.2 into the auxiliary power circuit bypass line 8c and out of the auxiliary power circuit. The cell unit 4.2 also has an associated positive auxiliary power circuit switch 6.2.3 and an associated negative auxiliary power circuit switch 6.2.4. The positive 6.2.3 and negative 6.2.4 auxiliary power circuit switches are arranged to: i) open to assist in switching the cell unit 4.2 into the auxiliary power circuit bypass line 8c and out of the auxiliary power circuit, and ii) close to assist in switching the cell unit 4.2 into the auxiliary power circuit and out of the auxiliary power circuit bypass line 8c.
In this embodiment, the cell unit 4.2 also has an associated group of switches on the positive side of the cell unit 4.2. In particular, there is provided a cell line switch 6.2.5 that is controlled to open or close in order to prevent a short circuit between adjacent cell units that are in different circuits (i.e. the main power circuit and the auxiliary power circuit). Typically, a cell line switch between adjacent cell units is controlled to: i) open if those cell units are switched into different circuits, and ii) close if those cell units are switched into the same circuit. Further, there is provided a first main power circuit switch 6.2.6 and a second main power circuit switch 6.2.7. The first main power circuit switch 6.2.6 may be provided between the cell line 8a and the main power circuit bypass line 8b and between the negative terminal of the preceding cell unit (not shown) and the cell line switch 6.2.5. The second main power circuit switch 6.2.7 may also be provided between the cell line 8a and the main power circuit bypass line 8b but between the positive terminal of the cell unit 4.2 and the cell line switch 6.2.5.

The first 6.2.6 and second 6.2.7 main power circuit switches are controlled in conjunction with the cell line switch 6.2.5 such that cell units 4 (such as individual cells or blocks of parallel-connected cells) can be switched into their appropriate circuit and entirely out of their inappropriate circuit without causing a short circuit. An example of this functionality is provided below.

Referring to Figure 1, the first 6.1.6 and second 6.1.7 main power circuit switches are not necessarily required for the first cell 4.1, as will become apparent from the discussion below. In other words, the first main power circuit switch 6.1.6, which is adjacent to the positive terminal of the external load 10 or power source, and the second main power circuit switch 6.1.7, which is adjacent to the positive terminal of the first cell unit 4.1, are not necessarily required. However, in this embodiment, the associated cell line switch 6.1.5 is still required. It will be appreciated that reducing the number of load switches reduces the complexity and cost of the battery balancing system.

A similar combination of switches 6 to that described above is typically provided for each cell unit 4 in the battery balancing system 2. Additionally, a ground switch (not shown) may be required adjacent to the external load 10 or power source negative terminal if the battery balancing system 2 is not grounded. Such a ground switch may be provided between the main power circuit negative rail 8d and ground (not shown).

Referring to Figures 3a, 3b and 3c, an example is illustrated in which cell units 4.1, 4.2, 4.4 are switched into the main power circuit (Figure 3a) and cell unit 4.3 is switched into the auxiliary power circuit (Figure 3b). It is noted that Figures 3a and 3b in combination
represent a single battery balancing system in operation with a complete main power circuit and a complete auxiliary power circuit, as illustrated in Figure 3c.

Referring to Figure 3a, a complete main power circuit including three series-connected cell units 4.1, 4.2, 4.4 is shown with a thick line. In particular, Figure 3a illustrates a complete main power circuit that provides power to an external load 10 during a discharge cycle. However, the external load 10 may be replaced with a power source during a charge cycle. To achieve this, the controller may control particular switches 6 to either open or close such that the external load 10 (or power source) is connected in series with series-connected cell units 4.1, 4.2, 4.4, which provides power to and a voltage difference over the external load 10 (or power from and a voltage difference over the power source). In particular, the controller controls each cell units’ 4.1, 4.2, 4.4 associated main power circuit bypass switch 6.1.1, 6.2.1, 6.4.1 to open, which means that the cell units 4.1, 4.2, 4.4 will not be switched into the main power circuit bypass circuit. Concurrently, the cell unit’s 4.3 associated main power circuit bypass switch 6.3.1 is controlled to close, which means that the cell unit 4.3 will bypass the main power circuit.

The controller may indirectly control the switches via opto-isolators or optocouplers and associated circuitry. For example, the controller may provide control signals to an optocoupler in electrical communication with each switch 6. Each optocoupler, upon receiving a control signal from the controller, can then control its associated switch to turn it on or off. This may be advantageous because it electrically isolates the power and switching circuitry from the controller, which could be damaged if there were a power surge, short circuit or other unexpected behaviour.

Generally, cell line switches 6.n.5 between adjacent cell units in the same circuit are controlled to close. In this example, cell line switches 6.1.5, 6.2.5 are controlled to close, because they are provided between adjacent cell units 4.1, 4.2 (or a load or power source) which are both in the same circuit (i.e. the main power circuit). This is in order to ultimately complete the main power circuit. Generally and conversely, cell line switches 6.n.5 between adjacent cell units that are not in the same circuit are controlled to open. In this example, cell line switch 6.3.5 is controlled to open, because it is provided between adjacent cell units 4.2, 4.3 that are not in the same circuit. Similarly, cell line switch 6.4.5 is controlled to open, because it is provided between adjacent cell units 4.3, 4.4 that are not in the same circuit. This is in order to ultimately bypass cell unit 4.3 from the main power circuit.

Finally, the first 6.n.6 and second 6.n.7 main power circuit switches must be appropriately controlled to complete the main power circuit while avoiding short circuits. In this example,
the cell unit's 4.3 associated first main power circuit switch 6.3.6 is controlled to close and second main power circuit switch 6.3.7 is controlled to open such that, in combination with the open associated cell line switch 6.3.5, a potential short circuit is avoided at this point. This combination of switch 6 states essentially blocks the cell unit's 4.3 positive terminal from being switched into the main power circuit. Concurrently, the cell unit's 4.4 associated first main power circuit switch 6.4.6 is controlled to open and second main power circuit switch 6.4.7 is controlled to close such that, in combination with the open associated cell line switch 6.4.5, a potential short circuit is avoided at this point. This combination of switch 6 states essentially blocks the cell unit's 4.3 negative terminal from being switched into the main power circuit.

This combination of switch 6 states causes cell units 4.1, 4.2, 4.4 to be connected in series with one another and the external load 10, hence completing the main power circuit such that power can be provided or drawn. It will be apparent from this example that the first 6.1.6 and second 6.1.7 main power circuit switches associated with the first cell unit 4.1 will have no effect on this circuit, whether open or close and regardless of which circuit cell unit 4.1 is in, and as such are not necessarily required.

Referring to Figure 3b, a complete auxiliary power circuit including cell unit 4.3 and an auxiliary load 12 is shown with a thick line. To achieve this, the controller may control particular switches 6 to either open or close such that the auxiliary load 12 is connected in series with series-connected cell unit 4.3, which provides power to and a voltage difference over the auxiliary load 12. In particular, the controller controls the cell unit's 4.3 associated auxiliary power circuit bypass switch 6.3.2 to open, which means that the cell unit 4.3 will not be switched into the auxiliary power circuit bypass circuit. Concurrently, the cell units' 4.1, 4.2, 4.4 associated auxiliary power circuit bypass switches 6.1.2, 6.2.2, 6.4.2 are controlled to close, which means that the cell units 4.1, 4.2, 4.4 will bypass the auxiliary power circuit.

The positive 6.n.3 and negative 6.n.4 auxiliary power circuit switches must be appropriately controlled to complete the auxiliary power circuit while avoiding short circuits. In this example, the cell units' 4.1, 4.2, 4.3 associated positive 6.1.3, 6.2.3, 6.4.3 and negative 6.1.4, 6.2.4, 6.4.4 auxiliary power circuit switches are controlled to open such that those cell units are completely bypassed. This combination of switch 6 states essentially blocks the cell units 4.1, 4.2, 4.4 from being switched into the auxiliary power circuit.

Finally, the cell unit's 4.3 associated positive 6.3.3 and negative 6.3.4 auxiliary power circuit switches are controlled to close such that the cell unit 4.3 is connected in series with the
auxiliary power circuit, hence completing the auxiliary power circuit such that power can be provided to the auxiliary load 12.

Figure 3c illustrates the completed main power circuit and the completed auxiliary power circuit on one circuit diagram. The two circuits are complete and isolated from one another.

The battery balancing system 2 allows for any required or desired combination of cell units 4 to be connected in series with one another and the external load 10 or power source, and concurrently allows for any required or desired combination of the remaining cell units 4 to be connected in series with one another and the auxiliary load 12, and concurrently allows for any still remaining cell units 4 to be switched out of either circuit. Thus, the battery balancing system allows for dynamic or active balancing of the cell units over time. The battery balancing system 2 may be scaled to any suitable size for any suitable application, such as a system comprising one hundred cell units 4 used to power an electric motor (i.e. external load 10) and a 12 V electric system (i.e. auxiliary load 12) of an electric vehicle.

Referring to Figure 4, in an embodiment, the battery balancing system 2 may comprise a plurality of auxiliary rail switches 18 associated with the auxiliary power circuit and a series of auxiliary rails 16. Figure 4 illustrates an embodiment comprising four cell units 4 (each having a voltage rating of 3V) and five auxiliary rails 16, but other embodiments may comprise and suitable number of cell units 4 and auxiliary rails 16. The auxiliary rail 16 voltage ratings are generally determined by the voltage ratings of the cell units 4. In this embodiment, the auxiliary rails comprise: i) a 12V auxiliary rail 16.1, ii) a 9V auxiliary rail 16.2, iii) a 6V auxiliary rail 16.3, iv) a 3V auxiliary rail 16.4, and v) a 0V auxiliary rail 16.5.

Generally, the positive side of each cell unit 4 has a plurality of associated auxiliary power switches 18 wherein each switch 18 is arranged to connect one of the first through the second-to-last auxiliary rails 16 to the cell line 8a. Similarly, the negative side of each cell unit 4 may have a plurality of associated auxiliary power switches wherein each switch 18 is arranged to connect one of the second through the last auxiliary rails 16 to the cell line 8a.

In particular in this embodiment, each cell unit 4 has eight associated auxiliary rail switches 18 wherein each switch 18 is arranged to connect its associated auxiliary rail 16 to the cell line 8a. The positive side of each cell unit 4 may have an associated: i) first auxiliary rail switch 18.n.1 arranged to connect the 12V auxiliary rail 16.1 to the cell line 8a, ii) second auxiliary rail switch 18.n.2 arranged to connect the 9V auxiliary rail 16.2 to the cell line 8a, iii) third auxiliary rail switch 18.n.3 arranged to connect the 6V auxiliary rail 16.3 to the cell line 8a, and iv) fourth auxiliary rail switch 18.n.4 arranged to connect the 3V auxiliary rail
16.4 to the cell line 8a. Similarly, the negative side of each cell unit 4 may have an
associated: i) fifth auxiliary rail switch 18.n.5 arranged to connect the 9V auxiliary rail 16.2
to the cell line 8a, ii) sixth auxiliary rail switch 18.n.6 arranged to connect the 6V auxiliary
rail 16.3 to the cell line 8a, iii) seventh auxiliary rail switch 18.n.7 arranged to connect the
3V auxiliary rail 16.4 to the cell line 8a, and iv) eighth auxiliary rail switch 18.n.8 arranged to
connect the 0V auxiliary rail 16.5 to the cell line 8a.

This configuration allows for connecting cell units 4 into and out of the auxiliary power
circuit without providing the auxiliary power circuit bypass switches of other embodiments
described above. This means that the auxiliary power circuit can be connected without
having current pass through a closed auxiliary power circuit bypass switch for each cell unit
4 that is not a part of the auxiliary power circuit, thus avoiding the voltage drop and power
loss caused by such switches.

An example of the operation of the embodiment of Figure 4 is provided below. The four cell
units 4.1, 4.2, 4.3, 4.4 are connected in series to provide 12V to the auxiliary load 12 and to
complete the auxiliary power circuit (shown with a thick line). Additional cell units that can
provide power to the external load 10 or receive power from the power source are not
illustrated in Figure 4.

In connecting or completing the auxiliary power circuit, the controller may control particular
auxiliary rail switches 18 to either open or close such that the auxiliary load 12 is connected
in series with series-connected cell units 4.1, 4.2, 4.3, 4.4, which provide power to and a
voltage difference over the auxiliary load 12. In this example, the controller controls the
first cell unit's 4.1 associated first auxiliary rail switch 18.1.1 to close such that the positive
side of the first cell unit 4.1 is electrically connected to the 12V auxiliary rail 16.1. The
controller also controls the first cell unit's associated fifth auxiliary rail switch 18.1.5 to close
so that the negative side of the first cell unit 4.1 is electrically connected to the 9V auxiliary
rail 16.2. In this configuration, the voltage difference provided by the first cell unit 4.1 (i.e.
3V in this example) is provided over the first 16.1 and second 16.2 auxiliary rails, thereby
defining a 3V potential difference therebetween.

The controller also controls auxiliary rail switches 18 associated with other cell units 4 that
are part of the auxiliary power circuit. In this example, the controller closes: i) the second
18.2.2 and sixth 18.2.6 auxiliary rail switches associated with the second cell unit 4.2 so
that it is connected between the 9V auxiliary rail 16.2 and the 6V auxiliary rail 16.3, ii) the
third 18.3.3 and seventh 18.3.7 auxiliary rail switches associated with the third cell unit 4.3
so that it is connected between the 6V auxiliary rail 16.3 and the 3V auxiliary rail 16.4, and
iii) the fourth 18.4.4 and eighth 18.4.8 auxiliary rail switches associated with the fourth cell
unit 4.4 so that it is connected between the 3V auxiliary rail 16.4 and the 0V auxiliary rail 16.5. This configuration completes the auxiliary power circuit by connecting the cell units 4 in series with one another and the auxiliary load 12 while avoiding the losses associated with the auxiliary power circuit bypass switches of other embodiments. In this example, the four cell units 4 provide 12V to the auxiliary load 12. Typically, any cell unit that is not a part of the auxiliary power circuit will have all of its associated auxiliary rail switches open.

The auxiliary rail switches may be controlled in any suitable manner such that a desired or required number of cell units 4 are connected in series with one another and the auxiliary load 12 to apply an appropriate voltage difference and provide power to the auxiliary load 12 via one or more auxiliary rails 16. Embodiments comprising the auxiliary rails 16 may comprise a main power circuit bypass switch 6.1, cell line switch 6.5, and first 6.6 and second 6.7 main power circuit switches associated with each cell unit 4. However, embodiments comprising the auxiliary rails 16 typically do not comprise the auxiliary power circuit bypass switch and the positive and negative auxiliary power circuit switches.

Referring to Figure 5, in an embodiment, the electrical connection mechanism associated with each cell unit 4 comprises a converter. Preferably, the converter is a DC-to-DC converter 14, which may be an isolated DC-to-DC converter. Each DC-to-DC converter 14 is typically provided as an isolated DC-to-DC converter and, as such, may comprise a high-frequency transformer, inverter and rectifier to provide an electrical isolation barrier. In addition, each DC-to-DC converter 14 typically comprises at least a switch, a diode and an inductor. A smoothing capacitor may also be provided on the auxiliary power circuit output side. The DC-to-DC converters 14 are controlled by the controller. The DC-to-DC converters 14 may be any suitable type of DC-to-DC converter, such as a buck converter.

In operation, the cell units 4 are connected in series with one another and the external load 10 or power source, such that a voltage difference and power may be supplied or drawn to respectively drive the external load 10 or charge the cell units 4. Initially, each DC-to-DC converter 14 may be deactivated; that is, controlled to not draw any power from its associated cell unit 4 (or not controlled at all). However, upon determining that a particular cell unit 4 has a non-average SOC, that cell unit’s 4 associated DC-to-DC converter 14 can be activated such that a desired amount of energy is drawn from the cell unit 4 and used to power the auxiliary load 12 and taken away from the external load 10 or removed from charging.

For example, during a charge cycle and upon activation of a cell unit’s associated DC-to-DC converter 14, energy will be drawn from the cell unit 4 and provided to the auxiliary load 12. This can cause the cell unit 4 to: i) charge slower than the other cell units 4 if the
charging current $I_{\text{charge}}$ is greater than the auxiliary power circuit current $I_{\text{aux}}$ (i.e. if $I_{\text{charge}} > I_{\text{aux}}$), ii) not charge if $I_{\text{charge}} = I_{\text{aux}}$, or iii) discharge if $I_{\text{charge}} < I_{\text{aux}}$. These three situations may help with battery balancing if the particular cell unit's 4 SOC was determined to be high.

5 During a discharge cycle and upon activation of a cell unit's associated DC-to-DC converter 14, energy will also be drawn from the cell unit 4 and provided to the auxiliary load 12. This will typically cause the cell unit 4 to discharge faster than the other cell units 4, which may help with battery balancing if the particular cell unit's 4 SOC was determined to be high. Conversely, if a particular cell unit's SOC is determined to be low, power can be drawn from the auxiliary power circuit to increase the cell unit's SOC in order to achieve battery balancing by activating that cell unit's associated DC-to-DC converter 14, in which case a bidirectional DC-to-DC converter 14 may be required. Alternatively, a cell unit 4 with a low SOC may be removed from the auxiliary power circuit and the main power circuit such that only high-SOC cell units 4 provide power, thereby lowering their SOC in order to achieve battery balancing.

In other embodiments, a single DC-to-DC converter 14 may be provided for a group of any suitable number of cell units 4 (such as individual cells or blocks of parallel-connected cells).

20 Any combination of suitable electrical connection mechanisms may be used. For example, an embodiment may have a first cell unit 4 with an associated electrical connection mechanism comprising a plurality of switches (as illustrated in Figure 1) and a second cell unit 4 with an associated electrical connection mechanism comprising a DC-to-DC converter 14 (as illustrated in Figure 5), and any other suitable electrical connection mechanisms associated with further cell units 4.

In other embodiments, the controller may be arranged to control the electrical connection mechanisms, such as the switches or DC-to-DC converters, to switch cell units into or out of the main power circuit or the auxiliary power circuit in order to set a cell unit's SOC as desired. For example, in an embodiment, each cell unit may have an associated temperature sensor (such as a thermocouple) arranged to provide the cell unit's real-time temperature to the controller. In this example, it is assumed that a cell unit with a high SOC that is switched into the main power circuit begins to overheat or starts showing an abnormal temperature increase. The controller, upon detecting such an abnormal temperature increase, may control the appropriate electrical connection mechanism to disconnect the cell unit from both the main power circuit and the auxiliary power circuit, thereby removing the cell unit from operation and allowing it to cool to a normal temperature. Upon reaching a normal temperature, the cell unit may be connected back
into an appropriate circuit. The controller may be arranged to make a record of the overheating incident or may signal the same to an operator.

In other embodiments, the controller may be arranged to control the electrical connection mechanisms to ensure that at any given moment an appropriate number of cell units are maintained with a high SOC so that the auxiliary load can be powered, for example, when the vehicle is parked but not charging. For example, in an embodiment with a 12V auxiliary load and 3V cell units, the controller may maintain four cell units with a high SOC by controlling those four cell units to slightly overcharge during a charging cycle. Certain embodiments of the invention are advantageous in that they provide a system and method that can be used to balance batteries or cell units while also providing power to both an external load and an auxiliary load, or alternatively while also charging the cell units and providing power to an auxiliary load. Embodiments of the invention may also be advantageous in that they provide a system and method that balances the batteries or cell units faster than the systems of the prior art. Embodiments of the invention may also be advantageous in that they provide a system and method with greater operational flexibility than the systems of the prior art.

The battery balancing system may be advantageous in that it can provide improved efficiency over passive and other active systems of the prior art. This typically corresponds to a range increase in electric vehicles. In fact, the inventors have found that a range increase of up to 7% may be provided by the battery balancing system in an electric vehicle with 100 series-connected cell units, of which four are used for a 12V to 16V auxiliary load. Indeed, the battery balancing system can provide nearly 100% efficiency when power output is close to zero, whereas systems of the prior art may only achieve 97.8% due to power losses in switches and cooling requirements. The battery balancing system may provide a 3% increase in efficiency in a system with 800 cells at an output of 20kW with low on-resistance switches (e.g. 1mΩ) when compared with the prior art.

The battery balancing system may be used for any suitable application. As well as in electrical vehicles, the battery balancing system may find application in a domestic or industrial multiple-kilovolt stationary battery storage system, which can power a high-voltage load on the primary (i.e. load / power source) side and simultaneously accept low voltage solar electricity on the secondary (i.e. auxiliary) side.

It will be understood to persons skilled in the art of the invention that voltage polarities referred to herein can be changed or reversed without departing from the spirit and scope of the invention.
In the claims that follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprise" or variations such as "comprises" or "comprising" is used in an inclusive sense, i.e. to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

It is to be understood that, if any prior art is referred to herein, such reference does not constitute an admission that such prior art forms a part of the common general knowledge in the art, in Australia or any other country.
Claims

1. A battery balancing system arranged to be electrically connected to an external load and an auxiliary load, the system comprising:
   a plurality of cell units, each being arranged to be connected in series with: i) the external load, or ii) the auxiliary load,
   a controller arranged to determine the state of charge of each of the cell units, and an electrical connection mechanism associated with each cell unit and arranged to be controlled by the controller based on the determined state of charge of the associated cell unit, wherein during a discharge cycle of the cell units each electrical connection mechanism is arranged to: i) electrically connect its associated cell unit to the external load in series with other cell units, ii) electrically connect its associated cell unit to the auxiliary load, alone or in series with other cell units, or iii) electrically disconnect its associated cell unit from the external load and the auxiliary load, in order to control the state of charge of each cell unit.

2. A battery balancing system as claimed in claim 1, wherein one or more of the electrical connection mechanisms is a DC-to-DC converter.

3. A battery balancing system as claimed in either claim 1 or 2, wherein one or more of the connection mechanisms is a plurality of switches.

4. A battery balancing system as claimed in claim 3, wherein each electrical connection mechanism comprises a main power circuit bypass switch arranged to operate to bypass its associated cell unit from a main power circuit upon determination that the cell unit is to be switched into an auxiliary power circuit.

5. A battery balancing system as claimed in either claim 3 or 4, wherein each electrical connection mechanism comprises a cell line switch arranged to: i) close to connect in series adjacent cell units or the first cell unit and the external load upon determination that such adjacent cell units or the first cell unit and the external load are to be switched into the same circuit, and ii) open to disconnect adjacent cell units or the first cell unit and the external load upon determination that such adjacent cell units or the first cell unit and the external load are to be switched into different circuits.

6. A battery balancing system as claimed in any one of claims 3 to 5, wherein each electrical connection mechanism comprises a first main power circuit switch and a second main power circuit switch arranged to switch their associated cell unit into a main power circuit.
7. A battery balancing system as claimed in any one of claims 3 to 6, wherein each electrical connection mechanism comprises an auxiliary power circuit bypass switch arranged to operate to bypass its associated cell unit from an auxiliary power circuit upon determination that the cell unit is to be switched into a main power circuit.

8. A battery balancing system as claimed in any one of claims 3 to 7, wherein each electrical connection mechanism comprises a positive auxiliary power circuit switch and a negative auxiliary power circuit switch arranged to switch their associated cell unit into an auxiliary power circuit.

9. A battery balancing system as claimed in any one of claims 3 to 6 comprising a plurality of auxiliary power rails arranged such that one or more cell units can be connected in series with the auxiliary load via the plurality of auxiliary rails.

10. A battery balancing system as claimed in any one of claims 1 to 9 comprising a master switch arranged to temporarily disconnect the external load, the auxiliary load or both from the cell units while the electrical connection mechanisms operate.

11. A battery balancing system arranged to be electrically connected to a power source, the system comprising:
    a plurality of cell units, each being arranged to be connected in series with the power source,
    a controller arranged to determine the state of charge of each of the cell units, and an electrical connection mechanism associated with each cell unit and arranged to be controlled by the controller based on the determined state of charge of the associated cell unit, wherein during a charge cycle of the cell units each electrical connection mechanism is arranged to: i) electrically connect its associated cell unit to the power source in series with other cell units, or ii) electrically disconnect its associated cell unit from the power source, in order to control the state of charge of each cell unit.

12. A battery balancing system as claimed in claim 11, wherein one or more of the electrical connection mechanisms is a DC-to-DC converter.

13. A battery balancing system as claimed in either claim 11 or 12, wherein one or more of the electrical connection mechanisms is a plurality of switches.

14. A battery balancing system as claimed in claim 13, wherein each electrical connection mechanism comprises a main power circuit bypass switch arranged to operate
to bypass its associated cell unit from a main power circuit upon determination that the cell unit is not to be switched into the main power circuit.

15. A battery balancing system as claimed in either claim 13 or 14, wherein each electrical connection mechanism comprises a cell line switch arranged to: i) close to connect in series adjacent cell units or the first cell unit and the power source upon determination that such adjacent cell units or the first cell unit and the power source are to be switched into the same circuit, and ii) open to disconnect adjacent cell units or the first cell unit and the power source upon determination that such adjacent cell units or the first cell unit and the power source are not to be switched into the same circuit.

16. A battery balancing system as claimed in any one of claims 13 to 15, wherein each electrical connection mechanism comprises a first main power circuit switch and a second main power circuit switch arranged to switch their associated cell unit into a main power circuit.

17. A battery balancing system as claimed in any one of claims 11 to 16 comprising a master switch arranged to temporarily disconnect the power source from the cell units while the electrical connection mechanisms operate.

18. An electric vehicle comprising the battery balancing system as claimed in any one of claims 1 to 17.

19. A battery balancing method comprising:
   determining a state of charge for each cell unit of a plurality of cell units,
   during a discharge cycle and based on the determined state of charge for each cell unit, controlling the electrical connection of each cell unit to: i) electrically connect it to an external load in series with other cell units, ii) electrically connect it to an auxiliary load, alone or in series with other cell units, or iii) electrically disconnect it from the external load and the auxiliary load, in order to control the state of charge of each cell unit.

20. A battery balancing method comprising:
   determining a state of charge for each cell unit of a plurality of cell units,
   during a charge cycle and based on the determined state of charge for each cell unit, controlling the electrical connection of each cell unit to: i) electrically connect it to a power source in series with other cell units, or ii) electrically disconnect it from the power source, in order to control the state of charge of each cell unit.
21. Computer program code which when executed implements the method of either claim 19 or 20.

22. A tangible readable memory comprising the computer program code of claim 21.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

H01M 10/44 (2006.01)  H02J 7/04 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC, Google Patents, inspec: battery, cell balancing, state of charge, switch and like terms; applicant and inventor name searched.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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Date of the actual completion of the international search: 22 October 2014

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<td>US 4616170 A (URSTÖGER) 07 October 1986 the whole of D1, in particular, fig.1, col.3 lines 41-46, col.5 lines 27-54, col.6 line 24 - col.7 line 20, col.7 line 52-col.8 line 3, col. 8 lines 30-32</td>
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