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(54) **CHARGE BALANCING SYSTEM**

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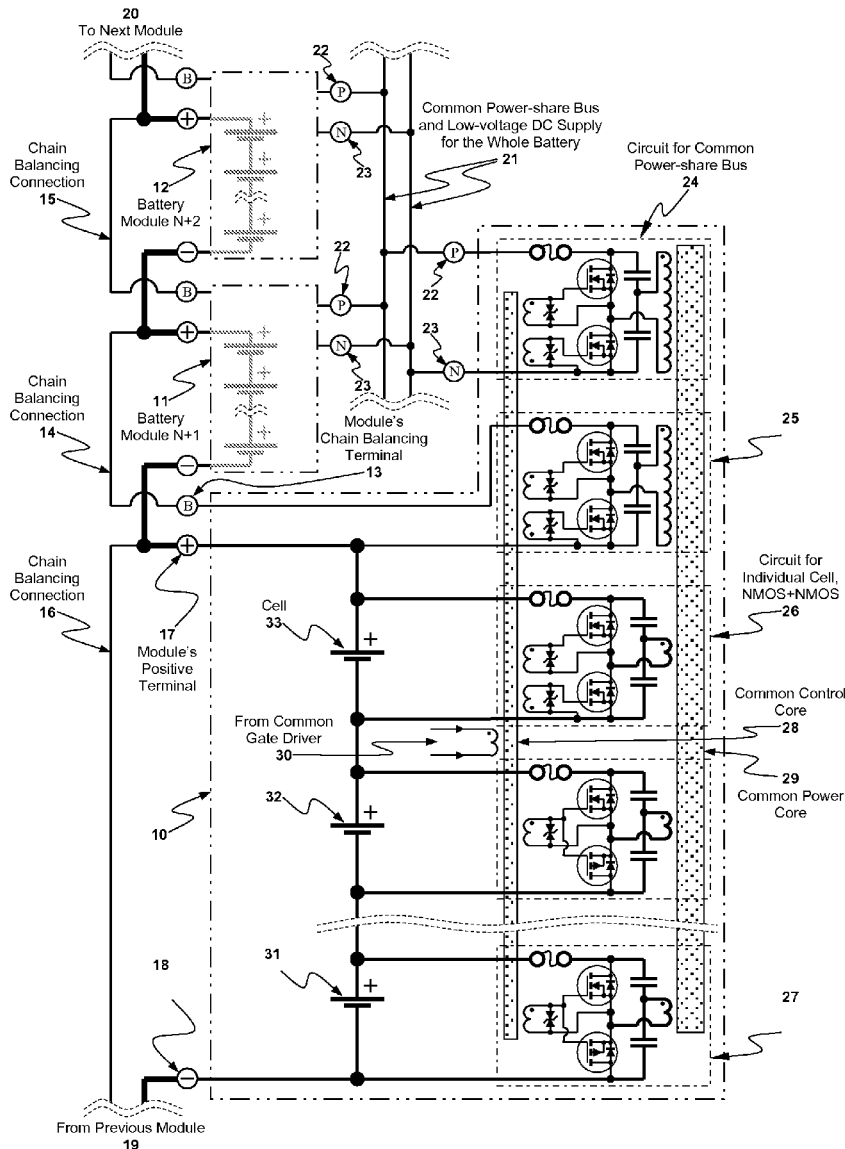
(57) **ABSTRACT**

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A method, circuit, and topology are provided for utilization of this circuit in Li-Ion or any other battery that benefits from balancing between individual cells. The whole system is characterized as having high efficiency (and thus low heat losses) compared to previous art implementations. The actions of the circuit are continuous and bi-directional in respect to each cell.

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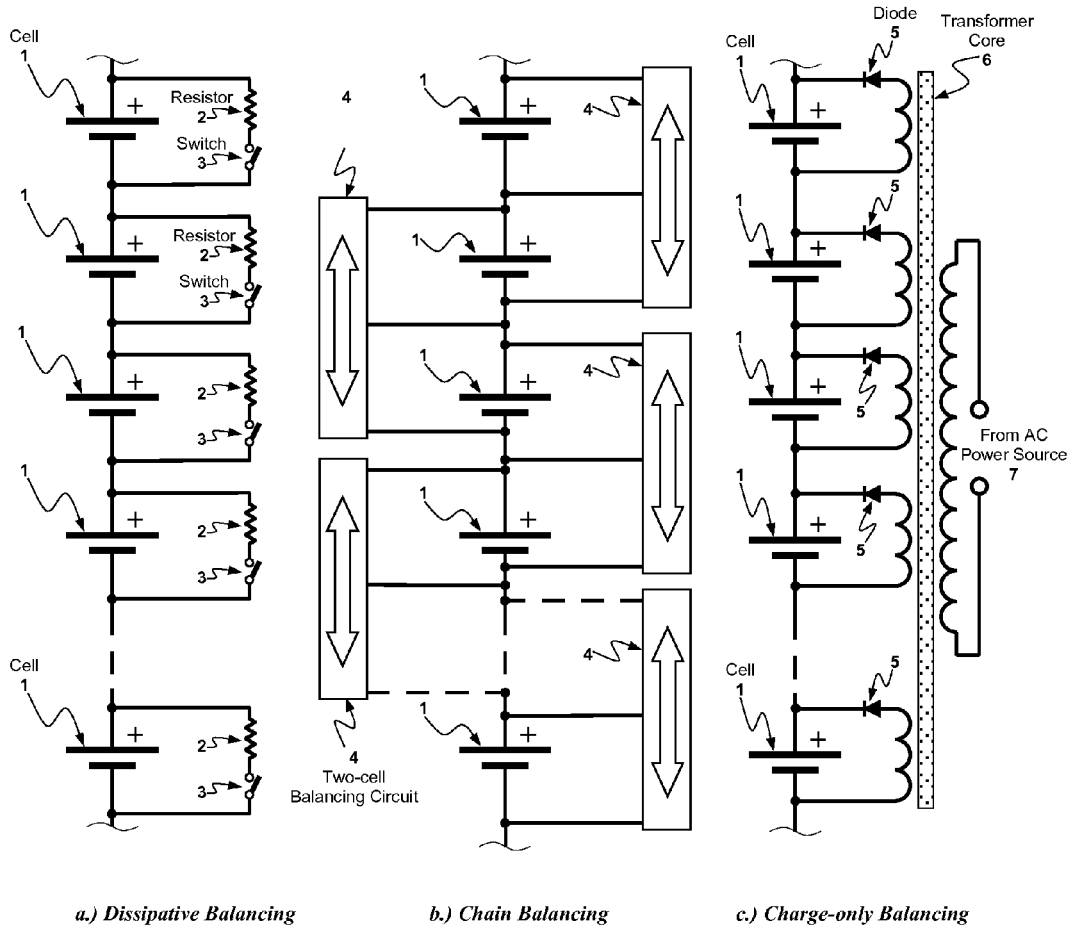


Figure 1 Prior Art

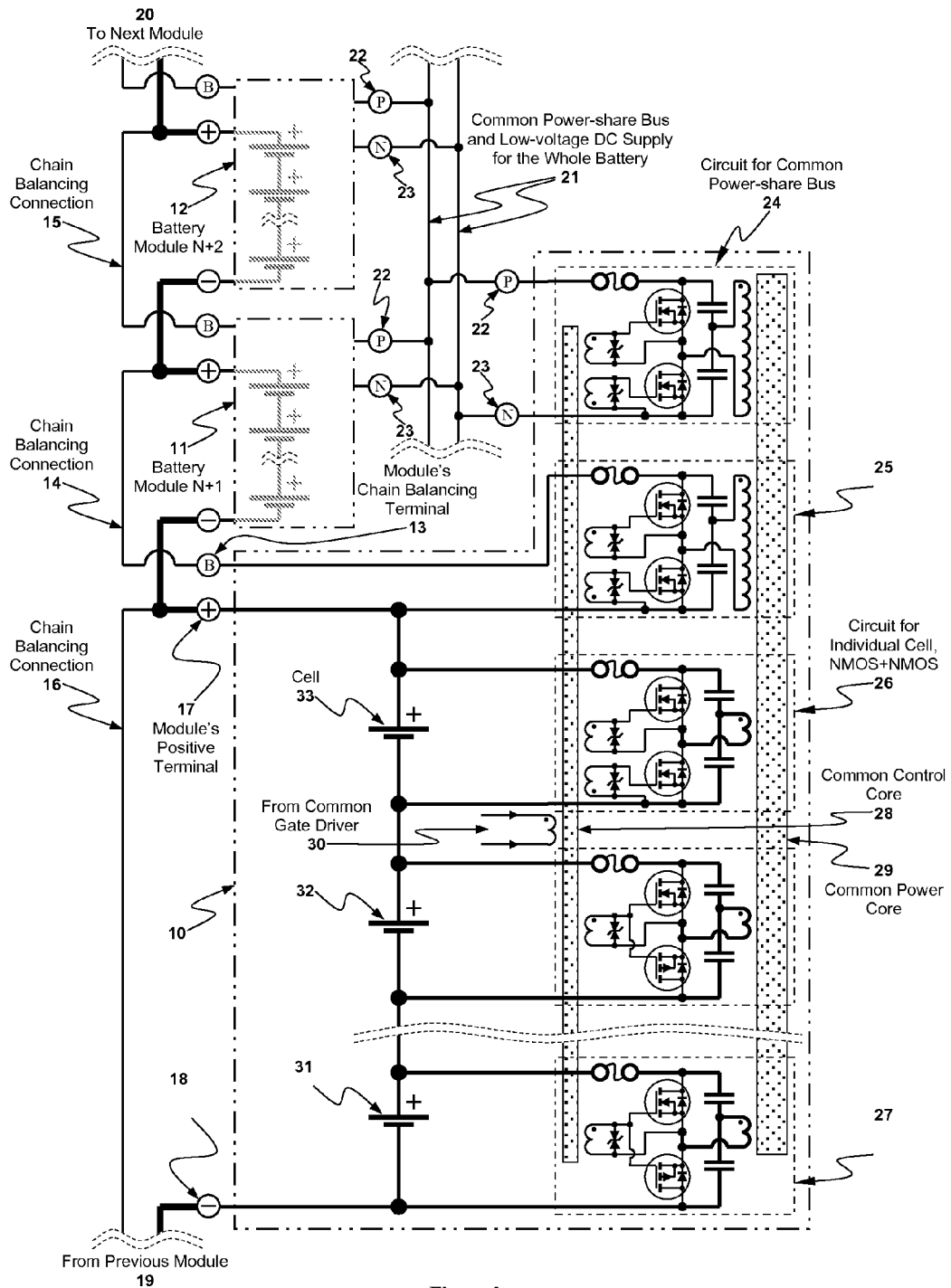


Figure 2

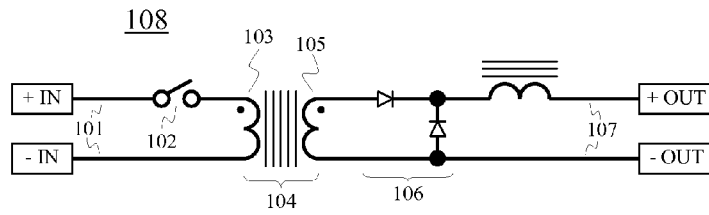


Figure 3

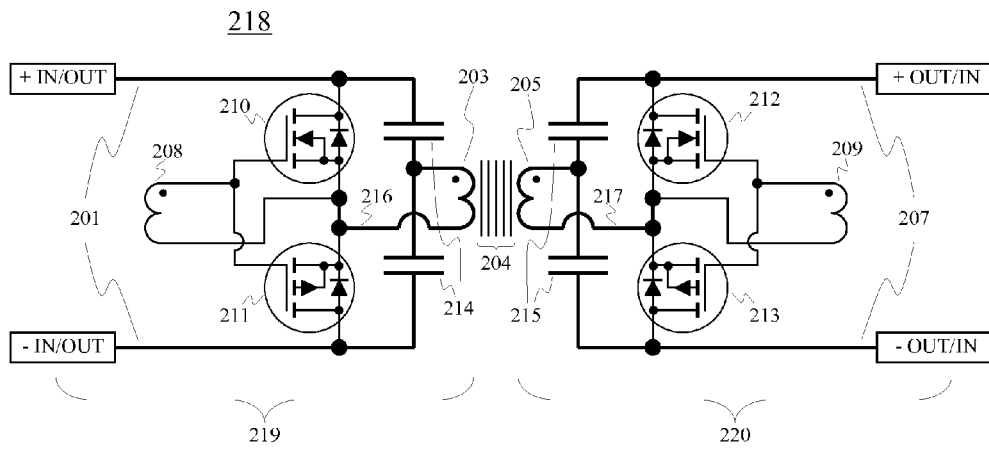


Figure 4

CHARGE BALANCING SYSTEM

BACKGROUND

[0001] Application of electrical energy in modern times often involves rechargeable batteries. Every household or place of business typically has several devices that operate from rechargeable batteries.

[0002] A promising technology for rechargeable batteries that has been employed in numerous applications is based on electro-chemical reactions involving Lithium. The so-called Lithium-Ion (Li-Ion) batteries of many different arrangements and material composition have been designed and used worldwide.

[0003] These batteries are typically lighter and store more energy in a given volume than the batteries based on the previous technologies, such as Lead-Acid, Nickel-Cadmium, etc.

[0004] The Lithium-chemistry batteries are, however, sensitive to over-charging that may lead to spontaneous and irreversible overheating and even fire/explosion.

[0005] At the same time, the Li-Ion cells are sensitive to over-discharge, as irreversible electro-chemical reactions take place and the cells quickly lose their ability to store charge (e.g. the capacity of the cells gets quickly reduced).

[0006] In order to store significant amounts of electrical energy, the individual Li-Ion cell are typically organized into batteries that contain series-connected cell. Since all the cells receive the same charging current, if a single cell reaches its maximum charge, the charging current must be stopped in order to prevent overcharging of that single cell. However, the rest of the cells will at that point not yet have received the full charge. After several charge/discharge cycles, it may well be that the whole battery becomes totally unusable, as some cells are totally discharged.

[0007] That is why it is typical that the Li-Ion battery includes some kind of equalization circuit that tries to “balance” the whole battery, allowing it to have useful life that is much longer than just several charge/discharge cycles, typically allowing hundreds or even thousands of cycles.

[0008] Thus the balancing circuit is an important building block for utilization of the Li-Ion batteries.

[0009] There are two types of balancing circuits, referring to the ability of the circuit to remove energy from one cell and deposit the energy in another cell (a so-called active balancing), and operations where the energy is simply dissipated as heat if a cell is close to overcharging (called passive or dissipative balancing).

[0010] An active balancing scheme is preferable not only due to the energy savings reasons (so as to reduce the energy costs), but also for the reduction of the heat generated in the battery; the heat having a detrimental effect on the useful life of the battery.

[0011] An example of passive balancing is shown in FIG. 1a.

[0012] Dissipative Balancing. A number of cells **1**, each cell having corresponding Resistor **2** and Switch **3** (that is typically a semiconductor device controlled by the monitoring circuitry), are connected in series. While charging, if a cell's potential gets close to the voltage that indicates full charge, at a time when the rest of the cells are not fully charged, a Switch **3** for that cell is activated (closed), and the current flowing via Resistor **2** discharges the cell. Depending on the magnitude of the discharge current flowing via Resis-

tor **2**, it may or may not be necessary to interrupt the “main” charging current through the whole battery.

[0013] Obviously, this method results in high heat losses. This method can produce a balanced state of the battery only while the battery is charging, and typically only for a condition of full charge. When the battery is discharged, as soon as one cell reaches the minimum allowed voltage potential, the whole battery is considered discharged and not able to provide any more energy. At the same time, other cells in the battery may well have significant amounts of energy left; however the Dissipative Balancing scheme does not allow recovery of this energy.

[0014] Another method is shown in FIG. 1b.

[0015] Chain Balancing. The two-cell balancing circuit **4** is able to transfer charge from one cell to the next cell in the series-connected stack of cells. While the method can formally be called “active balancing” due to energy transfer from one cell to the next (rather than dissipating the excess energy as heat), in reality the resulting heat losses during operations of the circuits of this type are high. It will be readily recognized that the energy transfer by this “chain” method is only efficient if the cells that need to be balanced are located close to each other in the series-connected string. On the other hand, if a cell with higher voltage is located relatively far from the cell that is having a lower voltage (e.g. having several cells in the chain between them), then the total efficiency for the power transfer will be the product of efficiency for all the transfers that are needed to move the energy from higher-charged cell to the lower-charged cell. For example, if the two-cell balancing circuit has 80% efficiency, and there are five cells between the cells that need to exchange the energy, then the resulting efficiency will only be about 26% ($0.8 * 0.8 * 0.8 * 0.8 * 0.8 = 0.262$).

[0016] In practical terms, there will be very little benefit in energy savings as compared with purely passive/dissipative balancing method, with significantly higher costs due to complexity of the two-cell balancing circuits.

[0017] Yet another active balancing scheme is depicted in FIG. 1c.

[0018] Charge-only Balancing. A transformer having multiple windings over Core **6** is utilized to charge all the cells at the same time, with a natural result that the voltage of all the cells is the same. This “simultaneous” charging can occur in addition to a larger charging current that is flowing through the series-connected cells in the battery. It will be recognized that the diodes **5** that are needed in this circuit will prevent operations with high efficiency due to non-zero forward voltage drop in the semiconductor diode; in addition, this type of circuits only permits the addition of energy to cells, and can only be deployed if the whole battery is somewhat discharged; it is unsuitable if one of the cells has to be discharged rather than charged.

[0019] Many active balancing approaches require measurement of the state of charge of each cell, and control or manipulation of the balancing system to bring about balancing. It would be helpful if an approach could be found that was self-adjusting and self-correcting and did not rely upon measurement of the state of charge of each cell.

[0020] It would be helpful if a way could be found to provide balancing between cells that is more efficient than prior-art approaches, and that can offer its benefits during charging times, discharging times, and idle times.

SUMMARY OF THE INVENTION

[0021] The current invention discloses a method, circuit, and topology for utilization of this circuit in Li-Ion or any

other battery that benefits from balancing between individual cells. The whole system is characterized as having high efficiency (and thus low heat losses) compared to previous implementations. In addition, the balancing of individual cells in the battery can be continuous, if so desired, and occurring throughout charging as well as discharging operations of the battery. All cells are balanced by either adding or removing the energy from each cell, as required in order to attain the balance between all the cells (e.g. the actions of the circuit are bi-directional). The fact of the permitted continuous operations allows each cell to be charged and discharged fully; this supports utilization of the previously unused cells' energy storage capacity resulting from manufacturing tolerances (e.g. varying cells' capacity even in a single manufacturing lot). Operations of the circuit do not require any intelligent controls besides simply turning the circuit on; the balancing processes are self-adjusting and self-correcting.

DESCRIPTION OF THE DRAWING

[0022] The current invention is disclosed with the aid of a drawing in several figures, of which:

[0023] FIG. 1 illustrates some prior-art circuits;

[0024] FIG. 2 shows an embodiment of the current invention;

[0025] FIG. 3 shows a prior-art forward converter; and

[0026] FIG. 4 shows an embodiment of a bidirectional forward converter.

DETAILED DESCRIPTION

[0027] It may be helpful to review the well-known basic forward converter **108** as shown in FIG. 3. It is a DC-to-DC converter with galvanic isolation provided by transformer **104**. Because there are very few lossy elements (no transistors half-on or half-off, for example, and very little ohmic resistance) the efficiency of the forward converter can be quite good.

[0028] Energy is passed from input **101** to output **107** during the times when current is changing in the transformer.

[0029] The voltage output at **107** from a forward converter is proportional to the turns ratio (secondary turns count at **105** divided by primary turns count at **103**) and to the duty cycle at the primary (defined by the behavior of switch **102**) and to the input voltage at **101**.

[0030] The forward converter **108** of FIG. 3 is, of course, not symmetric. It only passes energy from the input **101** to the output **107** and not the other direction.

[0031] Turning to FIG. 4, we see a forward converter **218** according to the invention. In this figure, the circuit is symmetric, meaning that the circuitry **219** and **220** are mirror images of each other, reflected about the transformer core **204**. As will be discussed further below, importantly either of connection points **201** and **207** can be an input or an output for purposes of the forward converter transfer function.

[0032] Windings **208** and **209** are control windings, providing an identically phased control signal to each of the circuits **219**, **220**, typically a square wave. Because the control currents are inductively coupled, they may be thought of as positive-going and negative-going excursions relative to nodes **216**, **217**, and thus they turn on transistor pairs **210**, **211** and **212**, **213** in alternation. For example during one excursion the "top" transistors **210**, **212** are on, and during the other excursion the "bottom" transistors **211**, **213** are on.

[0033] The turns counts are identical at the windings **203**, **205**, thus the turns ratio is unity.

[0034] The alert reader will thus begin to appreciate the interesting aspects of the circuits **219**, **220**. Each circuit behaves slightly differently depending on whether the voltage imposed upon it from outside is higher or lower as compared with the voltage imposed upon the other circuit from outside. Again in this example we have one rechargeable cell at **201** and another rechargeable cell at **207**, and the behavior of the circuit is different depending on the relative voltages at the two cells. If the cell at **201** is of slightly lower voltage compared with the cell at **207**, then it will tend to be on the receiving end of a forward converter function passing current to **201**. If the cell at **207** is of slightly lower voltage compared with the cell at **201**, then it will tend to be on the receiving end of a forward converter function passing current to **207**. In the case where the cells are at the same voltage, then little or no energy will pass one way or the other through the circuit **218**.

[0035] As a matter of terminology one might refer to each of circuits **219**, **220** as a "half-forward-converter" or "half-converter".

[0036] It will be appreciated that rectifying elements **106** in FIG. 3 bring about significant heat losses in circuit **108**, due to large forward voltage drop on the diodes. In contrast, the circuit **218** in FIG. 4 utilizes so-called Synchronous Rectifiers. It is not known in advance which of the parts **219/220** will perform the Synchronous Rectifier duty; this depends on the values of the voltages at **201** and **207**. As mentioned above, if these two voltages are exactly the same, the circuit **218** will not transfer energy in either direction.

[0037] Turning to FIG. 2, the battery is organized as a number of Modules (of which several are shown in the drawing, namely **10**, **11**, and **12**); each Module consists of a number of cells, such as **31**, **32**, and **33**.

[0038] Each cell has an associated balancing circuit that is coupled to all other balancing circuits within the Module (via Common Power Core **29**), and associated to other Modules either via Chain Balancing Terminals (such as **13**), or via Common Power-share Bus **21**.

[0039] The individual balancing circuits for each cell might be called Isolated Half-Bridge Forward Converters with Synchronous Rectifiers; the very same power transistors that perform a Half-Bridge duty (if the cell is having a higher voltage and thus is being discharged by sourcing the current) may be called to perform Synchronous Rectification duty if the cell is having a lower voltage (and is accepting the charging current). The transition from discharging to charging is automatic and does not require any controlling actions.

[0040] Two different possible configurations are shown, namely a circuit for individual cells with NMOS and PMOS transistors **27**, and a circuit with two NMOS transistors **26**.

[0041] All balancing circuits within a single Module share a single Power Core **29** and a single Control Core **28** that is used to provide the activating gate drive potentials to all the transistors. The signal from the Common Gate Driver **30** is simply a 50% duty cycle square wave of appropriate amplitude. Alternatively, the common gate driver circuit **30** may re-circulate the charge stored on the Gates of the transistors, in order to reduce the operating energy (losses) of the balancing circuits.

[0042] If the cells' voltage potentials are all the same, no charge or discharge current is flowing to or from any cell.

[0043] As a single Module would typically be constructed with 6-12 cells, the balancing action within the Module is

very effective, and efficiency of passing the charge from one cell inside the Module to any other cell inside the Module is equal to the efficiency of a single-stage Forward Converter with Synchronous Rectifiers. This efficiency can be as high as 95% or more.

[0044] On the other hand, if two Modules are connected via a chain balancing connection such as **14**, the energy transfer efficiency will be the somewhat lower, equal to the product of two-stage transfer, or 90% for the above-mentioned example of 95% efficiency for the individual circuits.

[0045] The same two-stage efficiency will be achieved if an exchange of energy is required between a cell in one Module and another cell that is located many cells away in the series-connected chain. In this case the energy will be transferred with the same two-stage efficiency as the chain balancing, with power flowing through the common power-share bus **21** via connection **22** and **23** that are coupled with circuit **24**.

[0046] Only one or both connections from chain balancing and common power-share balancing need be employed; the preference of one or another or both balancing links between the Modules of the whole battery depends on operating conditions and other practical considerations.

[0047] Returning to FIG. 4, the alert reader appreciates that there is no reason at all why the number of circuits **219**, **220** coupled with core **204** must be limited to two. In a battery module made up of ten cells in series, one could just as well provide ten circuits like **219**, one connected metallically to each of the cells, each circuit coupled to the core **204**. In this way the ten cells could be constantly balancing each other.

[0048] But the generalization does not stop with balancing among cells in a single battery module. Again returning briefly to FIG. 2, an entire battery module **11** can have its own circuit **25** which couples to a core **29**. The module can achieve balancing with individual cells such as **33**. It will be appreciated that the only circuit modifications that are needed to make this work are (a) selection of turns counts to maintain needed ratios, and (b) satisfaction of needed voltage ratings in selection of components such as the transistors.

[0049] A last area of generalization is that the connection point **201** (in FIG. 4) need not be to an individual cell (such as **33** in FIG. 2) and need not be to a battery module (such as module **11** in FIG. 2) but can be to a generalized metallic bus (such as **21** in FIG. 2). The bus could be at any desired DC level, so long as the turns count for its circuit (**24** in FIG. 2) is selected appropriately.

[0050] In one embodiment all of the balancing is cell to cell, mediated by a transformer core. In another embodiment modules are balanced with modules, again mediated by a transformer core. In another embodiment cells or modules are balanced with each other, mediated by cores connected by appropriate circuitry through a metallic bus. What these embodiments have in common is:

[0051] each element being balanced with other elements is galvanically isolated from those other elements; and

[0052] balancing takes place in an automatic and smooth way, not requiring explicit feedback or sensing circuitry.

[0053] As mentioned earlier the drive signal (at winding **30** in FIG. 2) is thought preferably to be a square wave. The goal is for each transistor of each half-converter to be either “on” or “off” and rarely if ever to be anywhere in between. This minimizes resistive losses within the transistors. What remains is to consider the frequency selected for this drive. As a general matter one would like the frequency to be relatively high, at least a few kilohertz or tens of kilohertz, because this

makes the transformer defined by core **29** (FIG. 2) or core **204** (FIG. 4) more efficient. Stated differently this permits the core to be reduced in size (and thus in weight) as compared with what would be needed if the drive were at a lower frequency.

[0054] On the other hand if the drive frequency were too high, this could result in “smearing” of the square wave drive signal as it passes through core **28** (FIG. 2) and eventually the desired lockstep in which all of the “top” transistors are on simultaneously, and are never on at the same time as any of the “bottom” transistors, might be lost at times.

[0055] It may be instructive to discuss the sizing of core **29** (FIG. 2) or core **204** (FIG. 4) as well as the choice of cross-sectional area for the wire employed in windings **203**, **205** (FIG. 4). The sizing decisions are based upon the amount of current that needs to be passed back and forth among cells and among cell modules, as the case may be. The current delivered to the load (at terminals **19**, **20** in FIG. 2 for example) can be quite large, for example providing acceleration power for an electric car; such current might be hundreds or even thousands of amperes.

[0056] In contrast, the currents required to achieve cell balancing might be relatively modest compared with the load current just mentioned. Thus the core sizing and wire cross-section choices may only need to support currents of a few amperes or perhaps fractions of an ampere. If the only balancing is cell balancing then the core and wire cross sections can be quite modest. If balancing on the module level is to be carried out as well, then the core and windings would need to be somewhat bigger, but still would not need to be so large as to support load currents.

[0057] The control core (**28** in FIG. 2) can be much smaller than the power core (**29** in FIG. 2). It only needs to generate voltages large enough to turn on the gates of the transistors **210**, **211**, **212**, **213**. The cells being balanced are described here in the context of electrochemical cells, but the balancing could be carried out with electrostatic cells, that is, capacitors.

[0058] The alert reader will have no difficulty devising myriad obvious improvements and variations of the invention, having been inspired by what is disclosed herein. All such improvements and variations are intended to be encompassed by the claims which follow.

1. Apparatus comprising:

- a power core;
- a control core;
- a gate driver driving the control core with a varying drive signal;

at least first and second half-converters, each half-converter inductively coupled with the power core and with the control core, each half-converter comprising:

- a first winding disposed for inductive coupling with the power core, the first winding having at least a first tap and a second tap;
- a second winding disposed for inductive coupling with the control core, the second winding having at least a first tap and a second tap;
- a first terminal and a second terminal, the first terminal and the second terminal connected by at least one semiconductor switch with the first winding;
- the at least one semiconductor switch having a control terminal, the control terminal of the semiconductor coupled with the second winding.

2. The apparatus of claim 1 further comprising, for each half-converter, a respective energy storage device having first

and second terminals, the first terminal of the half-converter conductively coupled with the first terminal of the respective energy storage device, and the second terminal of the half-converter conductively coupled with the second terminal of the respective energy storage device.

3. The apparatus of claim 2 wherein the respective energy storage devices are connected in series with each other.

4. The apparatus of claim 2 wherein the second terminal of the respective energy storage for the first half-converter is electrically connected with the first terminal of the respective energy storage for the second half-converter.

5. The apparatus of claim 2 wherein the respective energy storage device for each half-converter comprises an electrochemical cell.

6. The apparatus of claim 2 wherein the respective energy storage device for each half-converter comprises a battery comprising electrochemical cells in series.

7. The apparatus of claim 2 wherein the respective energy storage device for each half-converter comprises a capacitor.

8. The apparatus of claim 2 wherein the respective energy storage device for each half-converter comprises a module comprising capacitors in series.

9. The apparatus of claim 1 wherein the first half-converter is further characterized in that there are provided first and second semiconductor switches, each of the first and second semiconductor switches being an NMOS transistor having a gate and first and second power connections, the second tap of the first winding connected to the second power connection of the first switch and to the first power connection of the second switch and to the second tap of the second winding, the first terminal connected with the first power connection of the first switch and connected via a capacitor with the first tap of the first winding, the second terminal connected with the second power connection of the second switch and connected via a capacitor with the first tap of the first winding, the first tap of the second winding connected with the gate of the first switch;

the first half-converter further comprising a third winding disposed for inductive coupling with the control core, the third winding having at least a first tap and a second tap, the first tap of the third winding connected with the gate of the second switch, the second tap of the third winding connected with the second power connection of the second switch.

10. The apparatus of claim 1 wherein the first half-converter is further characterized in that there are provided first and second semiconductor switches, the first semiconductor switch being an NMOS transistor having a gate and first and second power connections, the second semiconductor switch being a PMOS transistor having a gate and first and second power connections, the second tap of the first winding con-

nected to the second power connection of the first switch and to the first power connection of the second switch and to the second tap of the second winding, the first terminal connected with the first power connection of the first switch and connected via a capacitor with the first tap of the first winding, the second terminal connected with the second power connection of the second switch and connected via a capacitor with the first tap of the first winding, the first tap of the second winding connected with the gate of the first switch and with the gate of the second switch.

11. The apparatus of claim 1 wherein the number of half-converters is at least six, each half-converter connected at its first and second terminals to a respective energy storage device, the respective energy storage devices electrically connected in series with each other.

12. The apparatus of claim 1 wherein the drive signal is at least thirty kHz.

13. The apparatus of claim 12 wherein the drive signal is at least one hundred kHz.

14. The apparatus of claim 13 wherein the drive signal is at least two hundred kHz.

15. The apparatus of claim 14 wherein the drive signal is at least one MHz.

16. A method for use with apparatus comprising a power core; a control core; a gate driver disposed for driving the control core with a varying drive signal; at least first and second half-converters, each half-converter inductively coupled with the power core and with the control core, each half-converter comprising: a first winding disposed for inductive coupling with the power core, the first winding having at least a first tap and a second tap; a second winding disposed for inductive coupling with the control core, the second winding having at least a first tap and a second tap; a first terminal and a second terminal, the first terminal and the second terminal connected by at least one semiconductor switch with the first winding; the at least one semiconductor switch having a control terminal, the control terminal of the semiconductor coupled with the second winding; the method comprising the steps of:

driving the control core with a varying drive signal.

17. The method of claim 16 wherein the drive signal is at least thirty kHz.

18. The method of claim 17 wherein the drive signal is at least one hundred kHz.

19. The method of claim 18 wherein the drive signal is at least two hundred kHz.

20. The method of claim 19 wherein the drive signal is at least one MHz.

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