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(54) Title: INDUCTOR-BASED ACTIVE BALANCING FOR BATTERIES AND OTHER POWER SUPPLIES

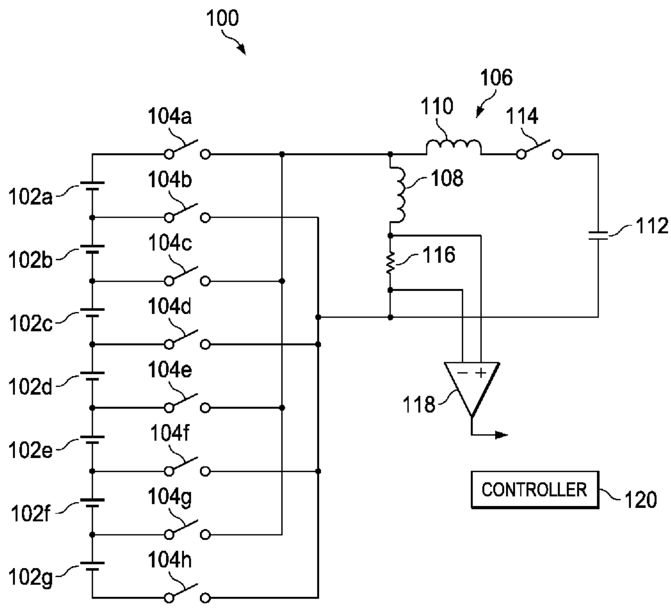

FIG. 1

(57) Abstract: A system includes multiple power supplies (102a-102g) connected in series and an active balancing circuit. The active balancing circuit includes an LC resonance circuit (106) and multiple switches (104a-104h) configured to selectively couple different ones of the power supplies to the LC resonance circuit. The LC resonance circuit includes an inductor (108), a capacitor (112), and an additional switch (114). The inductor is configured to store energy to be transferred between two or more of the power supplies. The additional switch is configured to selectively create a resonance between the inductor and the capacitor in order to reverse a direction of a current flow through the inductor. The active balancing circuit can transfer energy between individual power supplies or groups of power supplies.

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INDUCTOR-BASED ACTIVE BALANCING FOR BATTERIES AND OTHER POWER SUPPLIES

[0001] This is generally directed to power supply balancing systems and, more specifically, to inductor-based active balancing for batteries and other power supplies.

BACKGROUND

[0002] Modern batteries often include multiple battery cells connected in series, and multiple batteries can be connected in series to form a battery module. Unfortunately, the actual output voltage provided by each individual battery cell in a battery or each battery in a battery module may vary slightly. This can be caused by any number of factors, such as manufacturing variations, temperature variations, or other internal or external factors. This can cause problems during charging and discharging of the battery cells or batteries. In some systems, voltage detection circuitry can be used to determine the output voltage of each battery cell or battery, and a voltage balancing system can be used to compensate for variations in the output voltages.

[0003] Consider battery cells connected in series, where each battery cell is designed to provide an output voltage of 3.8V. Voltage detection circuitry may determine that one of the battery cells actually has an output voltage of 3.9V. A conventional passive voltage balancing system typically includes resistors that dissipate electrical energy from battery cells or batteries having excessive output voltage. In this example, the dissipation of electrical energy causes the 3.9V output voltage to drop to the desired level of 3.8V. However, since electrical energy is dissipated using the resistors, this can result in significant energy being lost from the battery cell, which shortens the operational life of the battery.

SUMMARY

[0004] Disclosed are methods and apparatus for inductor-based active balancing for batteries and other power supplies.

[0005] In a first embodiment, an apparatus includes an LC resonance circuit and multiple switches configured to selectively couple different power supplies connected in series to the LC resonance circuit. The LC resonance circuit includes an inductor, a capacitor, and an additional switch. The inductor is configured to store energy to be transferred between two or more of the power supplies. The additional switch is configured to selectively create a resonance between the inductor and the capacitor in order to reverse a direction of a current flow through the inductor.

[0006] In a second embodiment, a method includes transferring energy from at least one first power supply to an inductor. The method also includes selectively creating a resonance between the inductor and a capacitor in order to reverse a direction of a current flow through the inductor. The method further includes transferring the energy from the inductor to at least one second power supply. The at least one first power supply and the at least one second power supply are connected in series.

[0007] In a third embodiment, a system includes multiple power supplies connected in series and an active balancing circuit. The active balancing circuit includes an LC resonance circuit and multiple switches configured to selectively couple different ones of the power supplies to the LC resonance circuit. The LC resonance circuit includes an inductor, a capacitor, and an additional switch. The inductor is configured to store energy to be transferred between two or more of the power supplies. The additional switch is configured to selectively create a resonance between the inductor and the capacitor in order to reverse a direction of a current flow through the inductor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Example embodiments are described with reference to accompanying drawings, wherein:

[0009] FIG. 1 illustrates an example inductor-based active balancing system for batteries and other power supplies in accordance with this disclosure;

[0010] FIGS. 2A and 2B illustrate example operations of the system of FIG. 1 during odd-to-even and even-to-odd power transfers in accordance with this disclosure;

[0011] FIGS. 3A - 3D illustrate example operations of the system of FIG. 1 during odd-to-odd and even-to-even power transfers in accordance with this disclosure;

[0012] FIGS. 4A and 4B illustrate example operations of the system of FIG. 1 during power transfers involving multiple discharged power supplies and multiple charged power supplies in accordance with this disclosure;

[0013] FIGS. 5 and 6 illustrate example timing diagrams associated with simulated operations in the system of FIG. 1 during power transfers in accordance with this disclosure; and

[0014] FIG. 7 illustrates an example method for inductor-based active balancing for batteries and other power supplies in accordance with this disclosure.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0015] FIG. 1 illustrates an example inductor-based active balancing system 100 for batteries and other power supplies in accordance with this disclosure.

[0016] As shown in FIG. 1, the system 100 includes or is coupled to multiple power supplies 102a-102g connected in series. Each power supply 102a-102g represents any suitable source of power, such as a single battery cell. In particular embodiments, each power supply 102a-102g represents a single battery cell having a nominal voltage of 3.2V. However, each power supply 102a-102g could also represent multiple battery cells, a battery module, multiple battery modules, or other collection of battery cells. Any other types of power supplies could also be used, such as super-capacitors, fuel cells, and solar cells. Also note that any number of power supplies could be used here.

[0017] Multiple switches 104a-104h are coupled to the power supplies 102a-102g. The switches 104a-104h are opened and closed to transfer energy between selected power supplies 102a-102g via an inductor in an inductor-capacitor (LC) resonance circuit 106. The switches 104a-104h represent any suitable switching devices, such as transistors. In particular embodiments, each of the switches 104a-104h represents two back-to-back MOSFET transistors to prevent the short-circuit of two neighboring cells by the MOSFET body diode. Any single-switch devices with no body diodes can also be used here.

[0018] The LC resonance circuit 106 transfers energy between the selected power supplies 102a-102g. In this example, the LC resonance circuit 106 includes a first inductor 108, a second inductor 110, and a capacitor 112. As can be seen in FIG. 1, one end of the inductor 108 is connected to a first subset of the switches 104a-104h, and another end of the inductor 108 is connected to a second subset of the switches 104a-104h.

[0019] Each inductor 108-110 includes any suitable inductive structure having any suitable inductance. The inductance of the inductor 110 can be less (possibly much less) than the inductance of the inductor 108. In particular embodiments, the inductor 108 could have an inductance of 33μH, and the inductor 110 could have an inductance of 1μH. The capacitor 112 includes any suitable capacitive structure having any suitable capacitance. In particular embodiments, the capacitor 112 could have a capacitance of 1μF.

[0020] A switch 114 is coupled in series with the inductor 110 and with the capacitor 112. The switch 114 is used to selectively create a current path through the inductor 110 and the capacitor 112, thereby selectively controlling LC resonance in the circuit 106. The switch 114 represents any suitable switching device, such as at least one bi-directional transistor. In particular embodiments, the switch 114 represents two back-to-back MOSFET transistors.

[0021] A sense resistor 116 is coupled in series with the inductor 108 and to an amplifier 118. The inductor 108 and the sense resistor 116 are also coupled in parallel to the inductor 110, the capacitor 112, and the switch 114. A voltage across the sense resistor 116 varies depending on the current through the inductor 108. The sense resistor 116 includes any suitable resistive structure having any suitable resistance (typically a very small resistance). In particular embodiments, the sense resistor 116 could have a resistance of 0.1Ω. The amplifier 118 includes any suitable structure for amplifying a signal across a sense resistor, such as an LMP8601 amplifier available from Texas Instruments or other high common-mode voltage precision current sensing amplifier.

[0022] A controller 120 controls the overall operation of the system 100. For example, the controller 120 could receive signals from the amplifier 118. The controller 120 could also control the operation of the switches 104a-104h, 114 to control the charging and discharging of the power supplies 102a-102g. The controller 120 includes any suitable structure for controlling the charging and discharging of power supplies. For instance, the controller 120 could include a pulse width modulation (PWM) controller that generates control signals for the various switches, where the control signals have variable duty cycles controlled using PWM.

[0023] As described in more detail below, energy can be transferred from one or more of the power supplies 102a-102g to one or more other of the power supplies 102a-102g through the inductor 108. For example, energy can be discharged from one or more of the power supplies 102a-102g and stored in the inductor 108, and that energy can then be transferred to one or more other of the power supplies 102a-102g. If necessary, the direction of current flow through the inductor 108 can be reversed using a resonance created between the inductors 108-110 and the capacitor 112, allowing the transfer of energy between any of the power supplies.

[0024] In this way, the system 100 provides a novel and robust active balancing architecture. Direct balancing of energy can occur between power supplies without the need for an energy buffer (such as a transformer). This leads to higher balancing efficiency, such as up to 85% efficiency or more. Moreover, this active balancing approach represents an extremely low-cost solution since it uses one switch-pair per channel (power supply) and one larger inductor (inductor 108) per collection of power supplies. In addition, the system 100 provides more flexibility for system-level algorithms in that it can support a wide variety of multiple-supply charging/ discharging algorithms.

[0025] In the system 100 of FIG. 1, a distinction can be made between odd and even power supplies 102a-102g. Here, “odd” and “even” refer to the number assigned to the power supplies when they are numbered in series. In this example, power supplies 102a, 102c, 102e, and 102g could represent “odd” power supplies, and power supplies 102b, 102d, and 102f could represent “even” power supplies. This distinction is used since some energy transfers involve the use of the capacitor 112 while other energy transfers do not. In particular, power transfers from an odd-numbered power supply to an odd-numbered power supply (“odd-to-odd” transfers) and power transfers from an even-numbered power supply to an even-numbered power supply (“even-to-even” transfers) involve the capacitor 112. Power transfers from an odd-numbered power supply to an even-numbered power supply (“odd-to-even” transfers) and power transfers from an even-numbered power supply to an odd-numbered power supply (“even-to-odd” transfers) do not involve the capacitor 112.

[0026] Although FIG. 1 illustrates one example of an inductor-based active balancing system 100 for batteries and other power supplies, various changes may be made to FIG. 1. For example, any suitable number, type, or arrangement of power supplies could be used in the system 100. Also, various components in FIG. 1 could be rearranged as desired, such as by placing the switch 114 on the other side of the inductor 110. Further, additional components could be added to the system 100 according to particular needs. For instance, a 1nF or other capacitor could be coupled between the line joining the odd-numbered switches and ground, and a 300pF or other capacitor could be coupled between the line joining the even-numbered switches and ground. In addition, while specific circuit components are shown, other circuit components for performing the same or similar function(s) could be used.

[0027] FIGS. 2A and 2B illustrate example operations of the system 100 of FIG. 1 during odd-to-even and even-to-odd power transfers in accordance with this disclosure. In this particular example, a power transfer is occurring from power supply 102a to power supply 102d, making it an odd-to-even transfer. Similar operations may occur during an even-to-odd transfer. The opening and closing of the switches 104a-104h here is controlled by the controller 120.

[0028] As shown in FIG. 2A, in order to transfer energy out of the power supply 102a, two switches 104a-104b are closed, while the remaining switches 104c-104h are opened. This creates a current path 202 through the power supply 102a. Also, the switch 114 is opened to disconnect the capacitor 112 from the current path 202. This causes current to flow from the connected power supply 102a to the inductor 108, charging the inductor 108.

[0029] As shown in FIG. 2B, in order to transfer energy from the inductor 108 to the power supply 102d, two switches 104d-104e are closed, while the remaining switches 104a-104c, 104f-104h are opened. This creates a current path 204 through the power supply 102d. Also, the switch 114 remains opened. This causes current to flow from the inductor 108 to the connected power supply 102d, charging that power supply 102d. Note here that the currents through the inductor 108 flow in the same direction in FIGS. 2A and 2B.

[0030] FIGS. 3A - 3D illustrate example operations of the system 100 of FIG. 1 during odd-to-odd and even-to-even power transfers in accordance with this disclosure. In this particular example, a power transfer is occurring from power supply 102a to power supply 102c, making it an odd-to-odd transfer. Similar operations may occur during an even-to-even transfer. The opening and closing of the switches 104a-104h here is controlled by the controller 120.

[0031] As shown in FIG. 3A, in order to transfer energy out of the power supply 102a, two switches 104a-104b are closed, while the remaining switches 104c-104h are opened. This creates a current path 302 through the power supply 102a. Also, the switch 114 is opened to disconnect the capacitor 112 from the current path 302. This causes current to flow from the connected power supply 102a to the inductor 108, charging the inductor 108.

[0032] As shown in FIG. 3B, all of the switches 104a-104h are opened, and the switch 114 is closed. This causes current to flow from the inductor 108 to the capacitor 112 as part of a current flow 304. This current flow 304 transfers at least some of the energy stored on the inductor 108 to the capacitor 112.

[0033] As shown in FIG. 3C, all of the switches 104a-104h remain opened, and the switch 114 remains closed. This causes current to flow from the capacitor 112 to the inductor 108 during resonance as part of a current flow 306. After half of the resonate cycle time, the combined effect of the resonance in FIGS. 3B and 3C is to reverse the direction of current flow through the inductor 108.

[0034] As shown in FIG. 3D, in order to transfer energy from the inductor 108 to the power supply 102c, two switches 104c-104d are closed, while the remaining switches 104a-104b, 104e-104h are opened. This creates a current path 308 through the power supply 102c. Also, the switch 114 is opened. This causes current to flow from the inductor 108 to the connected power supply 102c, charging that power supply 102c. However, the current flows in the opposite direction through the inductor 108 than in FIG. 3A.

[0035] Note that while FIGS. 2A - 3D have dealt with the transfer of energy from a single power supply to a single power supply, transfers involving discharges from multiple power supplies and/or charges of multiple power supplies can also be performed.

[0036] FIGS. 4A and 4B illustrate example operations of the system 100 of FIG. 1 during power transfers involving multiple discharged power supplies and multiple charged power supplies in accordance with this disclosure. In this particular example, power is transferred from power supplies 102a-102c to power supplies 102d-102f. The opening and closing of the switches 104a-104h here is controlled by the controller 120.

[0037] As shown in FIG. 4A, in order to transfer energy out of the power supplies 102a-102c, the switches 104a, 104d are closed, while the remaining switches 104b-104c, 104e-104h are opened. This creates a current path 402 through the power supplies 102a-102c. Also, the switch 114 is opened to disconnect the capacitor 112 from the current path 402. This causes current to flow from the connected power supplies 102a-102c to the inductor 108, charging the inductor 108.

[0038] As shown in FIG. 4B, in order to transfer energy from the inductor 108 to the power supplies 102d-102f, the switches 104d and 104g are closed, while the remaining switches 104a-104c, 104e-104f, 104h are opened. This creates a current path 404 through the power supplies 102d-102f. Also, the switch 114 remains opened. This causes current to flow from the inductor 108 to the connected power supplies 102d-102f, charging those power supplies 102d-102f.

[0039] Although FIGS. 2A - 4B illustrate examples of the operations of the system 100 of FIG. 1 during different power transfers, various changes may be made to FIGS. 2A through 4B. For example, these FIGS. illustrate transfers between specific power supplies. Clearly, transfers between other power supplies or collections of power supplies could occur. Also, different combinations of these operations could be performed to transfer power between power supplies. For instance, power could be transferred from a single power supply to multiple power supplies or from multiple power supplies to a single power supply (with or without the use of the capacitor 112). In addition, note that in the implementation shown here, power can be transferred from an odd number of power supplies to the inductor 108, and power can be transferred from the inductor 108 to an odd number of power supplies (since closing the switches around an even number of power supplies would short-circuit those supplies). However, additional switches could be used to enable power transfers to or from an even number of power supplies, although this involves use of a larger number of switches.

[0040] FIGS. 5 and 6 illustrate example timing diagrams associated with simulated operations in the system of FIG. 1 during power transfers in accordance with this disclosure. In FIG. 5, a timing diagram 500 is associated with an odd-to-even or even-to-odd power transfer. In FIG. 6, a timing diagram 600 is associated with an odd-to-odd or even-to-even power transfer. These simulations are based on hysteretic control, where inductor current is sensed directly.

[0041] As shown in FIG. 5, a line 502 represents the control signal provided to the switch 114. This control signal pulses high periodically but does not create a resonance between the inductors 108-110 and the capacitor 112. Line 504 represents the control signal provided to the switches associated with at least one power supply to be discharged. Line 506 represents the control signal provided to the switches associated with at least one power supply to be charged. As can be seen here, the line 504 goes high approximately when the line 506 goes low, and the line 504 goes low approximately when the line 506 goes high.

[0042] Line 508 represents the current through the inductor 108. Lines 510-512 represent the currents through the at least one discharging power supply and the at least one charging power supply, respectively. As can be seen here, the line 504 goes high and the line 506 goes low to transfer energy into the inductor 108, and the line 504 goes low and the line 506 goes high to transfer energy out of the inductor 108. The current through the inductor 108 increases during the time that the at least one discharging power supply is transferring energy to the inductor 108. The current through the inductor 108 decreases during the time that the at least one charging power supply is receiving energy from the inductor 108.

[0043] As shown in FIG. 6, a line 602 represents the control signal provided to the switch 114. Line 604 represents the control signal provided to the switches associated with at least one power supply to be discharged. Line 606 represents the control signal provided to the switches associated with at least one power supply to be charged. Line 608 represents the current through the inductor 108, and lines 610-612 represent the currents through the at least one discharging power supply and the at least one charging power supply, respectively. In addition, line 614 represents the voltage across the sense resistor 116.

[0044] As can be seen here, line 602 goes high between the line 604 going low (when the charging of the inductor 108 ends) and the line 606 going high (when the discharging of the inductor 108 begins). During this time period, the direction of current flow through the inductor 108 is reversed using the resonance created between the inductors 108-110 and the capacitor 112.

[0045] Although FIGS. 5 and 6 illustrate examples of timing diagrams associated with simulated operations in the system 100 of FIG. 1 during power transfers, various changes may be made to FIGS. 5 and 6. For example, these timing diagrams are for illustration only, and the waveforms shown here could vary depending on the specific implementation of a given circuit. As particular examples, the various pulse widths and pulses heights shown here in the signals could vary.

[0046] FIG. 7 illustrates an example method 700 for inductor-based active balancing for batteries and other power supplies in accordance with this disclosure. As shown in FIG. 7, at least one power supply to be charged is identified at step 702, and at least one power supply to be discharged is identified at step 704. This could include, for example, the controller 120 identifying the power supply or supplies 102a-102g having the highest output voltage(s) and identifying the power supply or supplies 102a-102g having the lowest output voltage(s).

[0047] The switches associated with the at least one power supply being discharged are closed at step 706. This could include, for example, the controller 120 closing the pair of switches around the power supply or power supplies 102a-102g having the highest output voltage(s). Energy is transferred from the at least one power supply being discharged to an inductor at step 708. This could include, for example, the power supply or power supplies 102a-102g having the highest output voltage(s) transferring at least some of their energy to the inductor 108. The switches associated with the at least one power supply being discharged are opened at step 710. This stops the transfer of energy to the inductor 108.

[0048] A decision is made whether the current path through the inductor needs to be reversed at step 712. This could include, for example, the controller 120 determining whether the power transfer involves an odd-to-odd or even-to-even transfer. If so, a control switch is closed to create a resonance with the inductor at step 714. This could include, for example, the controller 120 closing the switch 114 to create a resonance between the inductors 108-110 and the capacitor 112. This reverses the direction of the current flow through the inductor at step 716. This could include, for example, transferring at least some of the energy from the inductor 108 to the capacitor 112 and then back to the inductor 108. The control switch is opened at step 718.

[0049] The switches associated with the at least one power supply being charged are closed at step 720. This could include, for example, the controller 120 closing the pair of switches around the power supply or power supplies 102a-102g having the lowest output voltage(s). Energy is transferred from the inductor to the at least one power supply being charged at step 722. This could include, for example, the inductor 108 transferring at least some of its stored energy to the power supply or power supplies 102a-102g having the lowest output voltage(s). The switches associated with the at least one power supply being charged are opened at step 724. This stops the transfer of energy from the inductor 108.

[0050] In this way, the method 700 supports the direct balancing of energy between power supplies without the need for an energy buffer, which can lead to higher balancing efficiency. Moreover, this approach requires fewer components to implement compared to conventional balancing approaches, and a wide variety of algorithms can be used to select the power supplies to be charged and discharged.

[0051] Although FIG. 7 illustrates one example of a method 700 for inductor-based active balancing for batteries and other power supplies, various changes may be made to FIG. 7. For example, while shown as a series of steps, various steps in FIG. 7 could overlap, occur in parallel, occur in a different order, or occur multiple times. As a particular example, the method 700 could be performed repeatedly for different combinations of power supplies until all of the power supplies have substantially equal output voltages.

[0052] Note that the system 100 shown above could be used in any type of system in which active balancing of power supplies is required or desired. For instance, the system 100 could be used with the power supplies in electric vehicles or hybrid electric vehicles, such as to balance lithium ion batteries or other types of batteries. Any other device or system that uses multiple power supplies could also include the system 100. Also note that any particular values (such as inductances, capacitances, resistances, and efficiencies) given above may represent exact or approximate values and are related to specific implementations of a circuit.

[0053] Those skilled in the art to which this relates will appreciate that modifications may be made to the described examples, and also that many other embodiments are possible, within the scope of the claimed invention.

CLAIMS

What is claimed is:

1. An apparatus comprising:

an LC resonance circuit; and

multiple switches configured to selectively couple different power supplies connected in series to the LC resonance circuit;

wherein the LC resonance circuit comprises:

an inductor configured to store energy to be transferred between two or more of the power supplies;

a capacitor; and

an additional switch configured to selectively create a resonance between the inductor and the capacitor in order to reverse a direction of a current flow through the inductor.

2. The apparatus of Claim 1, further comprising a controller configured to control the multiple switches and the additional switch in order to control the transfer of the energy between the two or more power supplies.

3. The apparatus of Claim 2, wherein, in order to transfer the energy from a first of the power supplies to a second of the power supplies, the controller is configured to:

close a first pair of the multiple switches to transfer the energy from the first power supply to the inductor;

open the first pair of the multiple switches; and

close a second pair of the multiple switches to transfer the energy from the inductor to the second power supply.

4. The apparatus of Claim 2, wherein, in order to transfer the energy from a first of the power supplies to a second of the power supplies, the controller is configured to:

close a first pair of the multiple switches to transfer the energy from the first power supply to the inductor;

open the first pair of the multiple switches;

close the additional switch to create the resonance and reverse the direction of the current flow through the inductor;

open the additional switch; and

close a second pair of the multiple switches to transfer the energy from the inductor to the second power supply.

5. The apparatus of Claim 2, wherein, in order to transfer the energy between a first group of the power supplies and a second group of the power supplies, the controller is configured to:

close a first pair of the multiple switches to transfer the energy from the first group of power supplies to the inductor;

open the first pair of the multiple switches; and

close a second pair of the multiple switches to transfer the energy from the inductor to the second group of power supplies.

6. The apparatus of Claim 1, wherein:

the inductor comprises a first inductor; and

the LC resonance circuit further comprises a second inductor coupled in parallel with the first inductor.

7. The apparatus of Claim 6, wherein:

the first inductor is coupled in series with a sense resistor;

the capacitor and the additional switch are coupled in series with the second inductor; and

the capacitor, the additional switch, and the second inductor are coupled in parallel with the first inductor and the sense resistor.

8. The apparatus of Claim 7, wherein:

a first end of the first inductor is connected to a first subset of the multiple switches; and

a second end of the first inductor is connected to a second subset of the multiple switches.

9. The apparatus of Claim 8, wherein:
the first subset includes only odd-numbered switches; and
the second subset includes only even-numbered switches.

10. A method comprising:
transferring energy from at least one first power supply to an inductor;
selectively creating a resonance between the inductor and a capacitor in order to reverse a direction of a current flow through the inductor; and
transferring the energy from the inductor to at least one second power supply, the at least one first power supply and the at least one second power supply connected in series.

11. The method of Claim 10, wherein:
transferring the energy from the at least one first power supply to the inductor comprises using a first pair of multiple switches;
transferring the energy from the inductor to the at least one second power supply comprises using a second pair of the multiple switches; and
selectively creating the resonance between the inductor and the capacitor comprises using an additional switch.

12. The method of Claim 11, wherein transferring the energy from the at least one first power supply to the inductor and transferring the energy from the inductor to the at least one second power supply comprise:
closing the first pair of the multiple switches to transfer the energy from the first power supply to the inductor;
opening the first pair of the multiple switches; and
closing the second pair of the multiple switches to transfer the energy from the inductor to the second power supply.

13. The method of Claim 11, wherein transferring the energy from the at least one first power supply to the inductor, selectively creating the resonance, and transferring the energy from the inductor to the at least one second power supply comprise:

closing the first pair of the multiple switches to transfer the energy from the first power supply to the inductor;

opening the first pair of the multiple switches;

closing the additional switch to create the resonance and reverse the direction of the current flow through the inductor;

opening the additional switch; and

closing the second pair of the multiple switches to transfer the energy from the inductor to the second power supply.

14. The method of Claim 11, wherein transferring the energy from the at least one first power supply to the inductor and transferring the energy from the inductor to the at least one second power supply comprise:

closing the first pair of the multiple switches to transfer the energy from a first group of power supplies to the inductor;

opening the first pair of the multiple switches; and

closing the second pair of the multiple switches to transfer the energy from the inductor to a second group of power supplies.

15. A system comprising multiple power supplies connected in series; and

an active balancing circuit comprising:

an LC resonance circuit; and

multiple switches configured to selectively couple different ones of the power supplies to the LC resonance circuit;

wherein the LC resonance circuit comprises:

an inductor configured to store energy to be transferred between two or more of the power supplies;

a capacitor; and

an additional switch configured to selectively create a resonance between the inductor and the capacitor in order to reverse a direction of a current flow through the inductor.

16. The system of Claim 15, wherein the active balancing circuit further comprises a controller configured to control the multiple switches and the additional switch in order to control the transfer of the energy between the two or more power supplies.

17. The system of Claim 16, wherein, in order to transfer the energy from a first of the power supplies to a second of the power supplies, the controller is configured to:

close a first pair of the multiple switches to transfer the energy from the first power supply to the inductor;

open the first pair of the multiple switches; and

close a second pair of the multiple switches to transfer the energy from the inductor to the second power supply.

18. The system of Claim 16, wherein, in order to transfer the energy from a first of the power supplies to a second of the power supplies, the controller is configured to:

close a first pair of the multiple switches to transfer the energy from the first power supply to the inductor;

open the first pair of the multiple switches;

close the additional switch to create the resonance and reverse the direction of the current flow through the inductor;

open the additional switch; and

close a second pair of the multiple switches to transfer the energy from the inductor to the second power supply.

19. The system of Claim 16, wherein, in order to transfer the energy between a first group of the power supplies and a second group of the power supplies, the controller is configured to:

close a first pair of the multiple switches to transfer the energy from the first group of power supplies to the inductor;

open the first pair of the multiple switches; and

close a second pair of the multiple switches to transfer the energy from the inductor to the second group of power supplies.

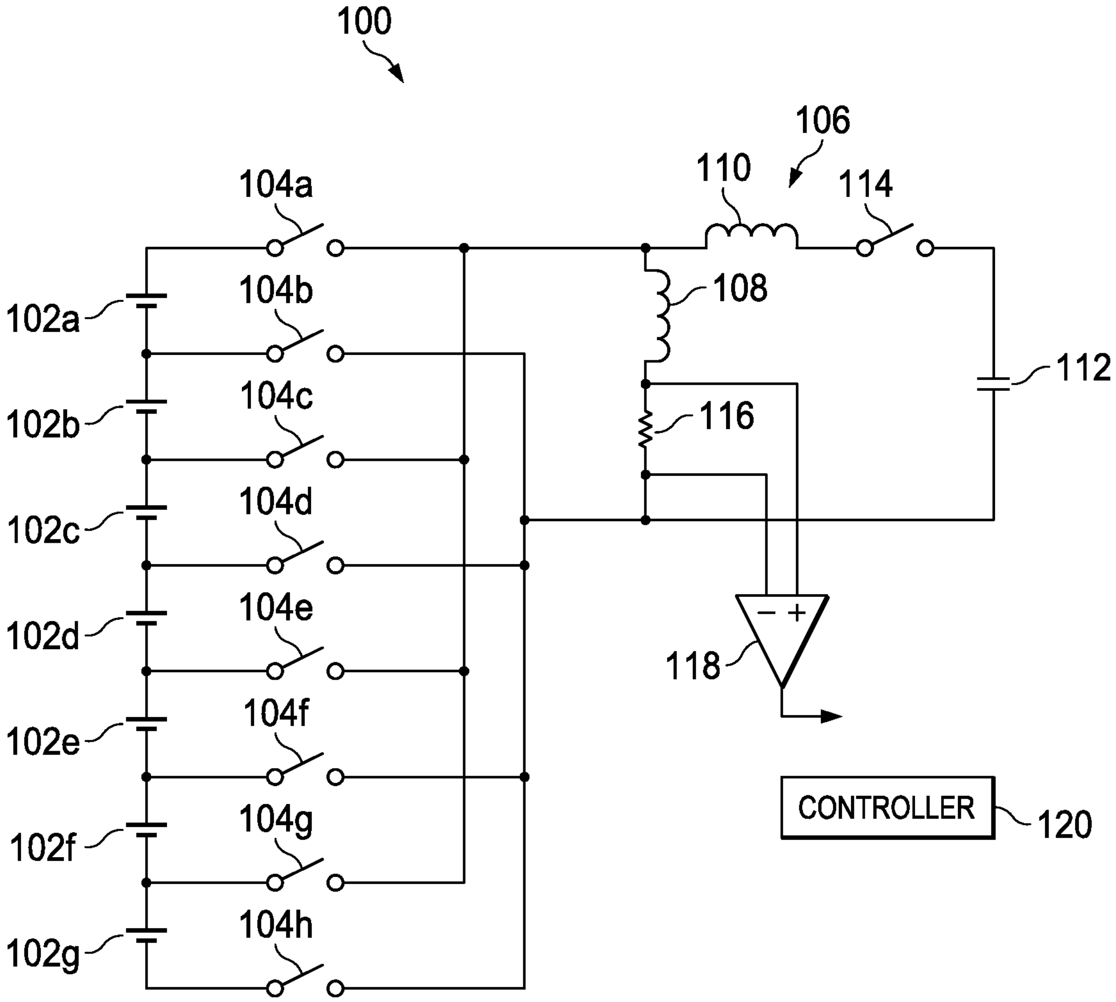
20. The system of Claim 15, wherein:

the inductor comprises a first inductor;

the LC resonance circuit further comprises a sense resistor and a second inductor;

the first inductor is coupled in series with the sense resistor;

the capacitor and the additional switch are coupled in series with the second inductor; and the capacitor, the additional switch, and the second inductor are coupled in parallel with the first inductor and the sense resistor.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102g
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112
116
118
CONTROLLER
120

FIG. 1

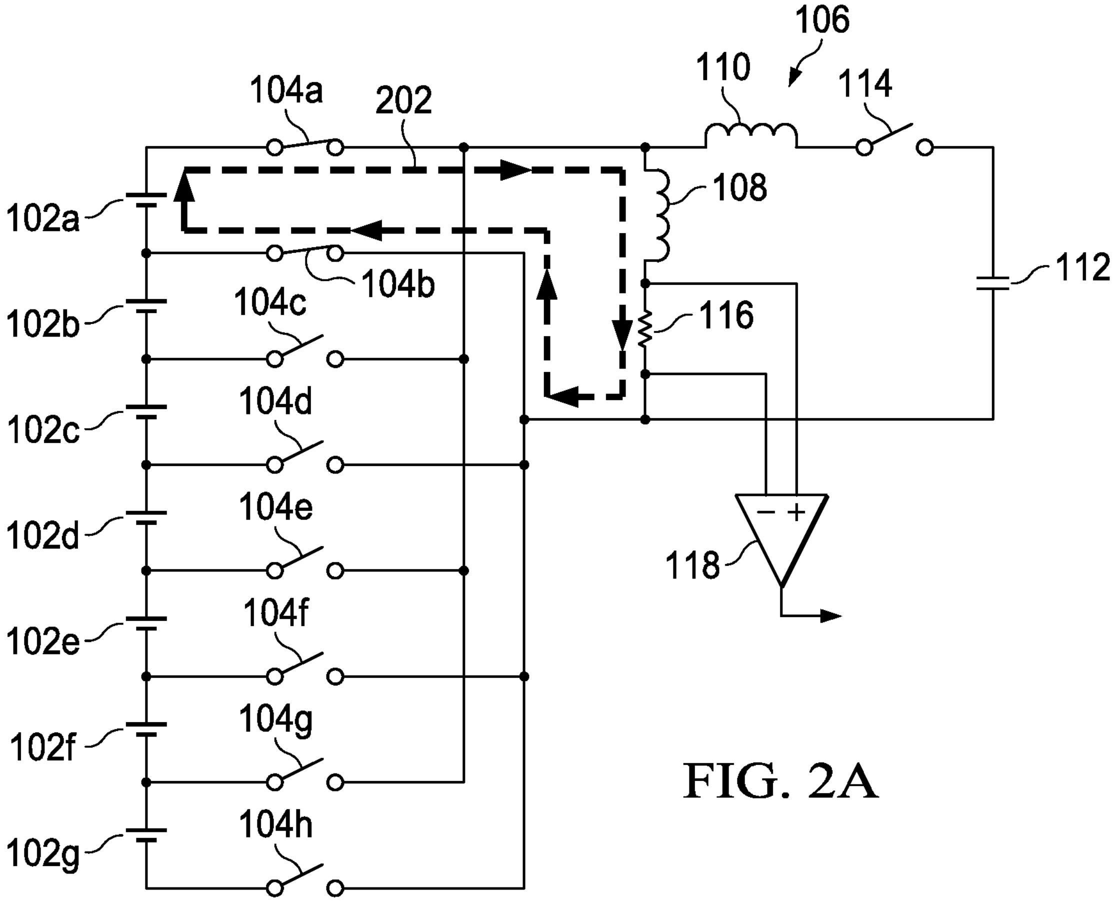
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FIG. 2A

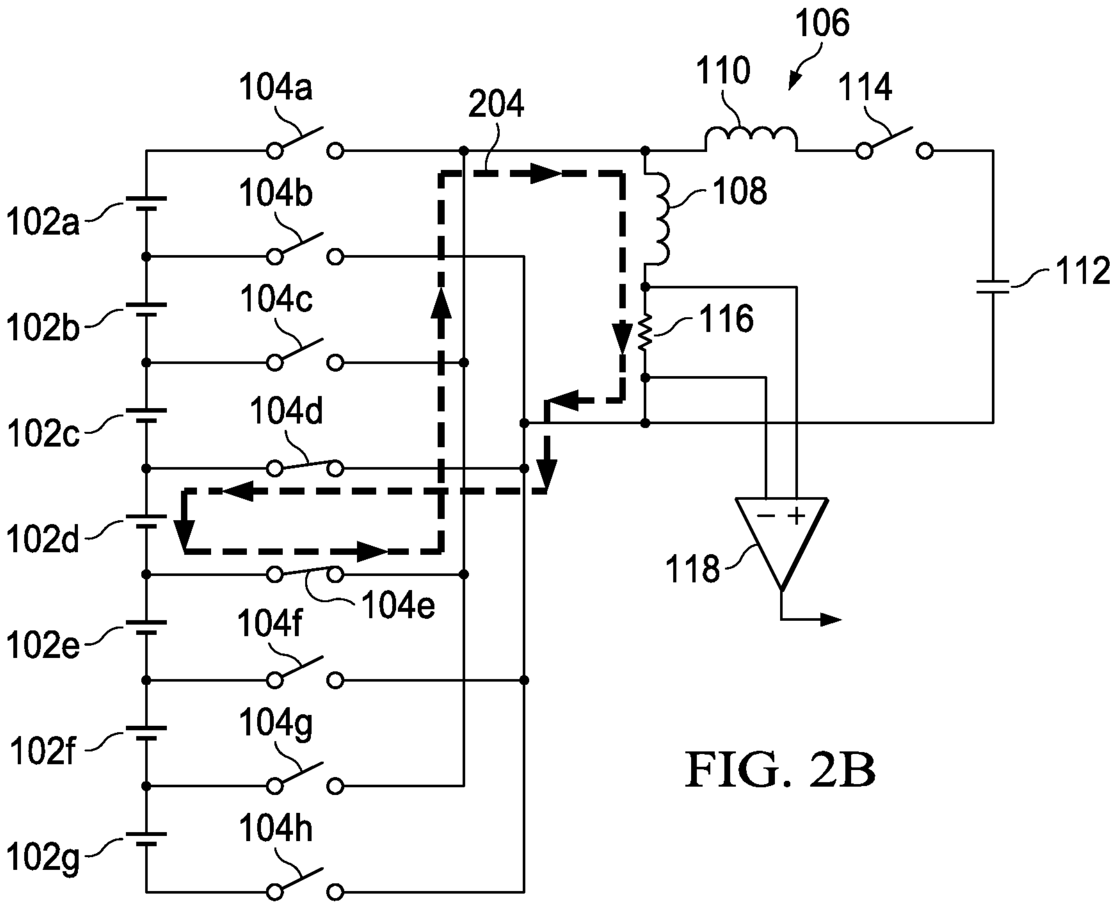
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FIG. 2B

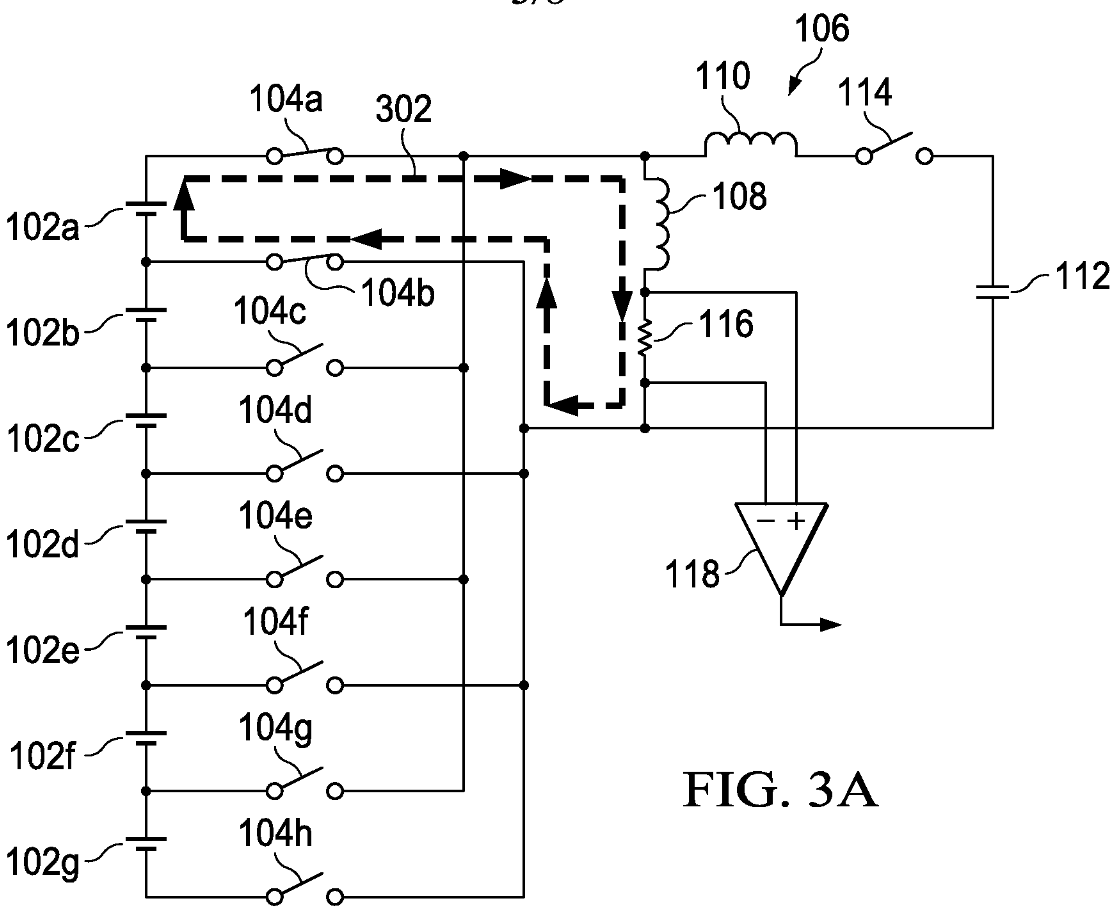
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FIG. 3A

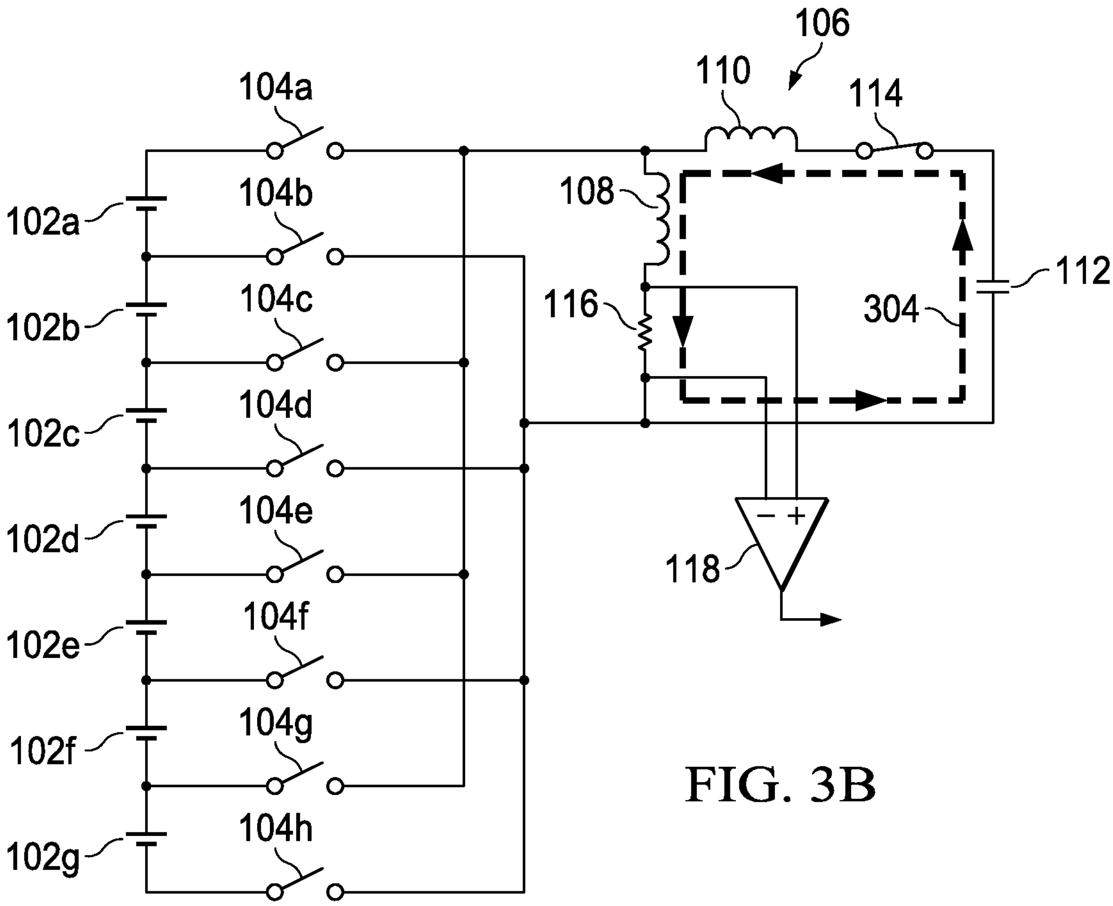
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FIG. 3B

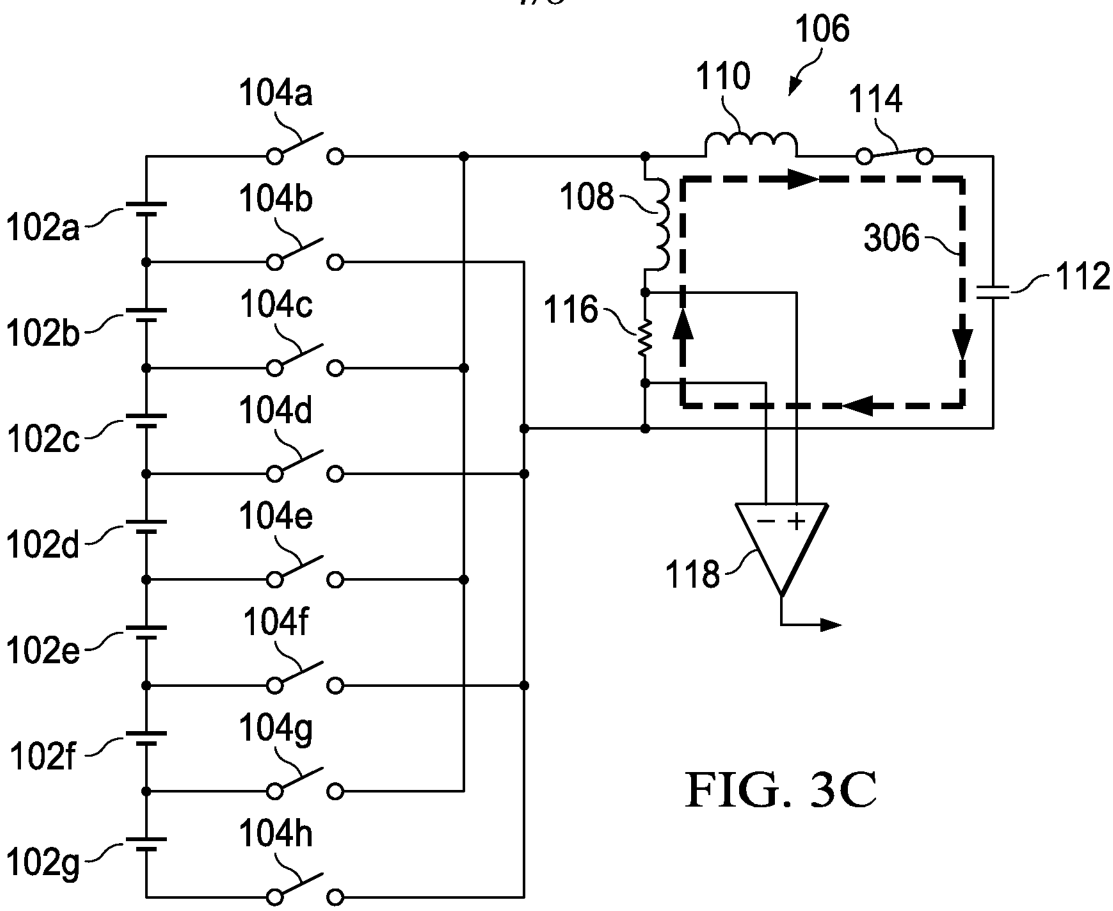
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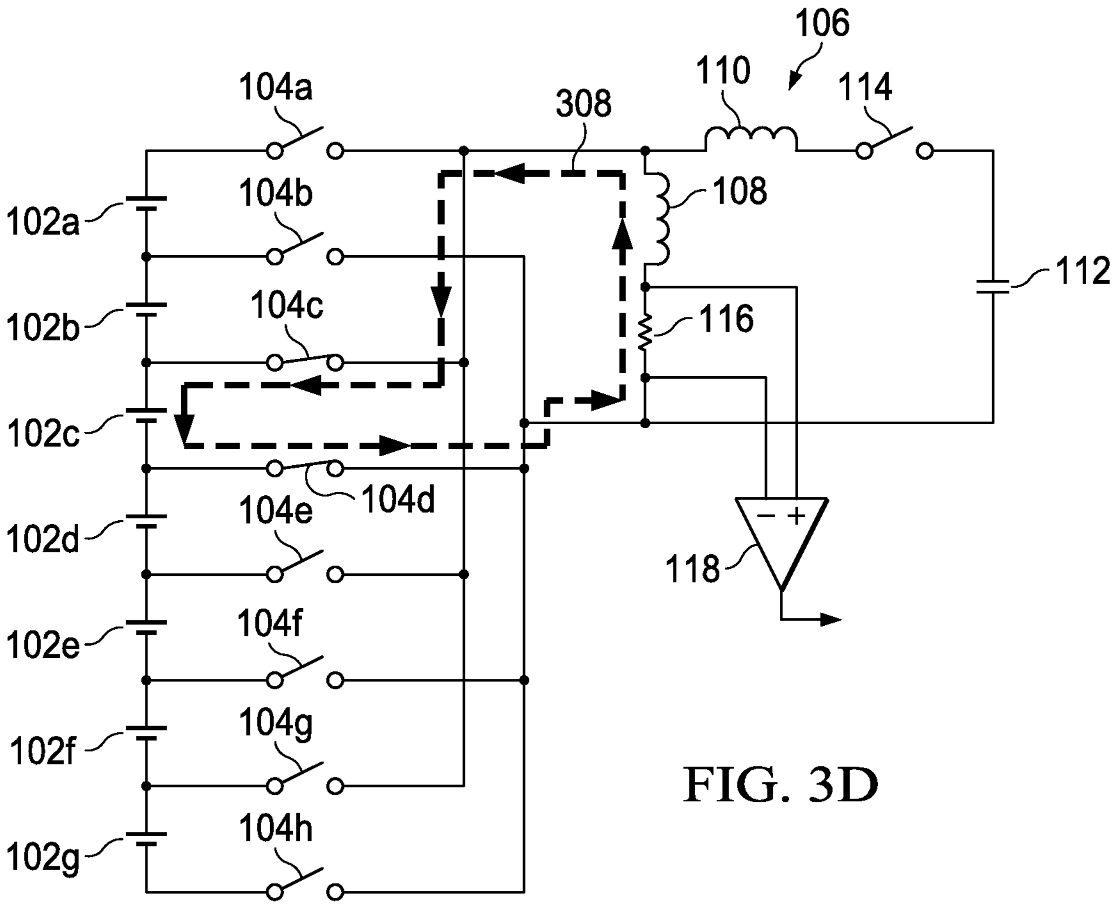
FIG. 3C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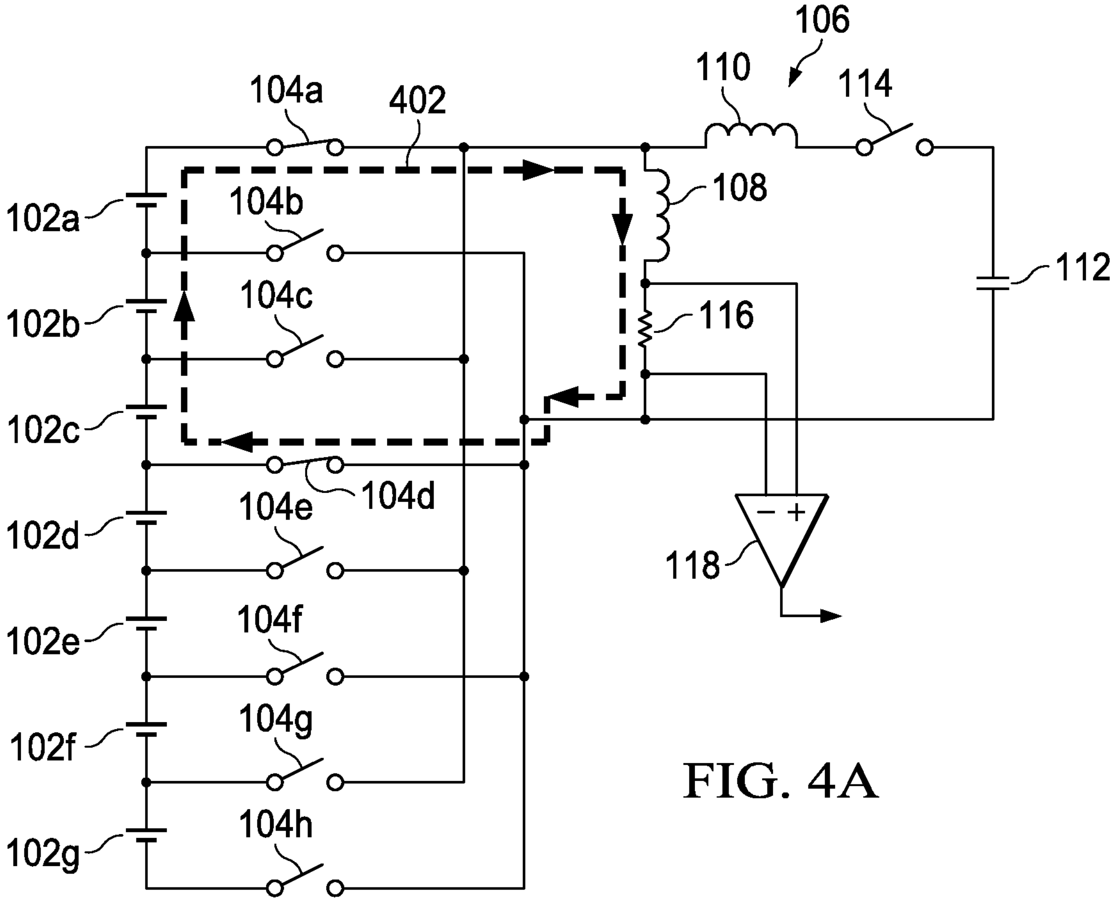
118
− +

FIG. 3D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102f
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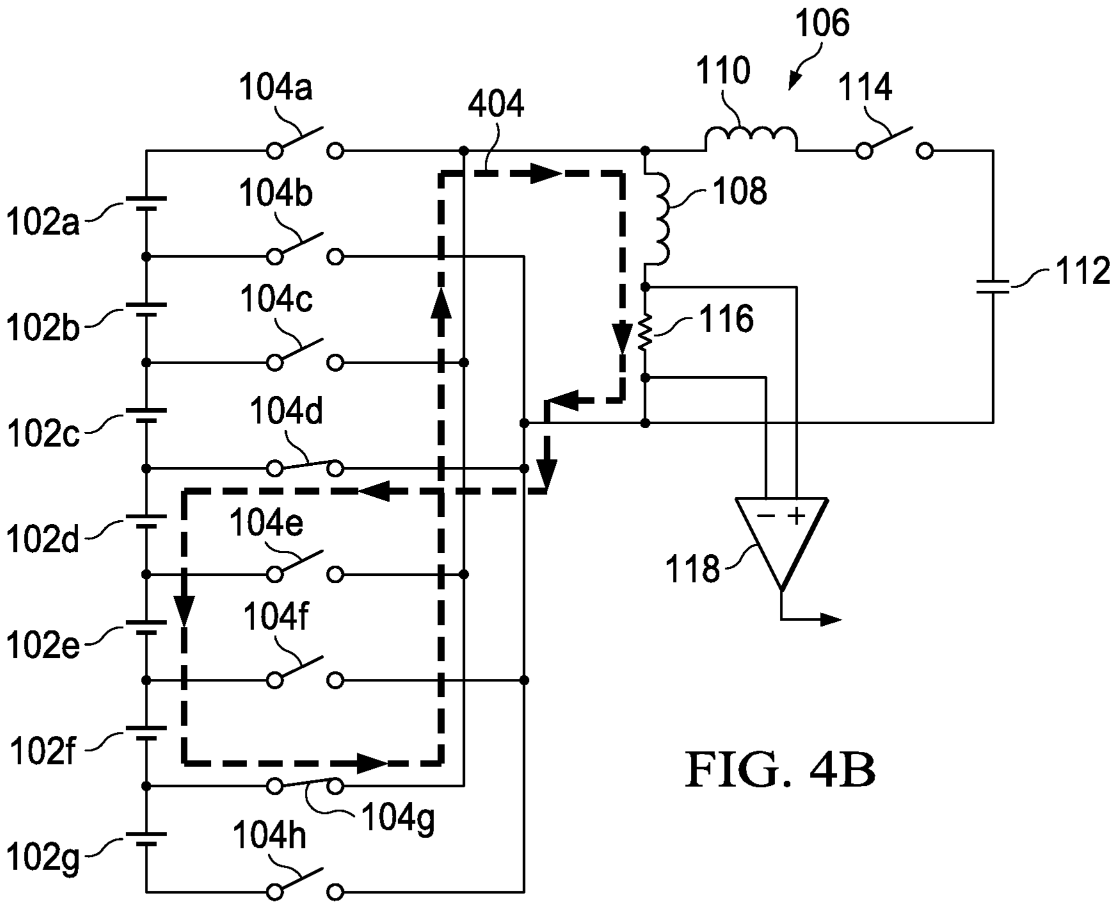
102g
104h

FIG. 4A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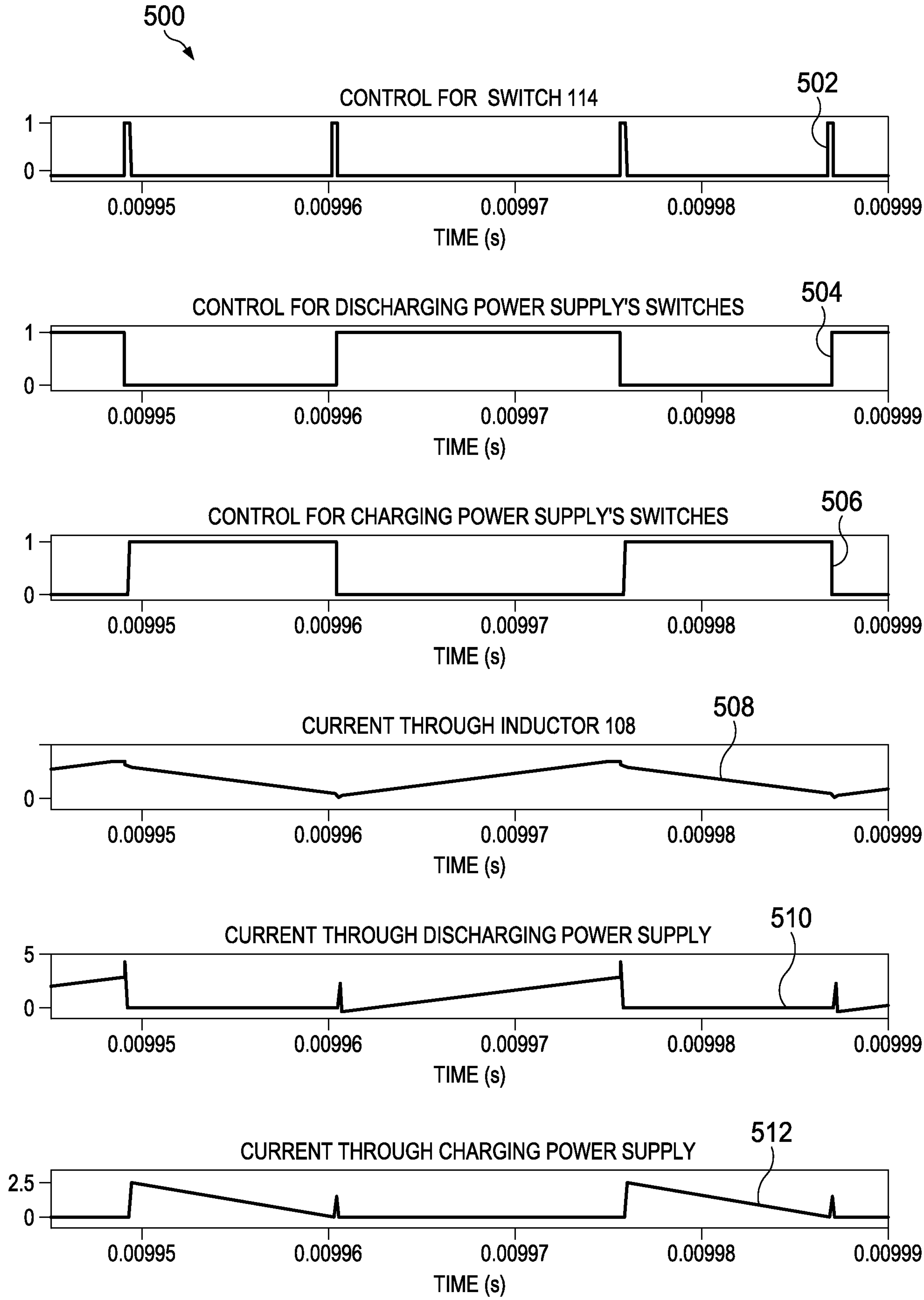
102f
104g
102g
104h

FIG. 4B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CONTROL FOR SWITCH 114
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0.00995
0.00996
0.00997
0.00998
0.00999
TIME (s)
CONTROL FOR DISCHARGING POWER SUPPLY'S SWITCHES
504
1
0
0.00995
0.00996
0.00997
0.00998
0.00999
TIME (s)
CONTROL FOR CHARGING POWER SUPPLY'S SWITCHES
506
1
0
0.00995
0.00996
0.00997
0.00998
0.00999
TIME (s)
CURRENT THROUGH INDUCTOR 108
508
0
0.00995
0.00996
0.00997
0.00998
0.00999
TIME (s)
CURRENT THROUGH DISCHARGING POWER SUPPLY
510
5
0
0.00995
0.00996
0.00997
0.00998
0.00999
TIME (s)
CURRENT THROUGH CHARGING POWER SUPPLY
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2.5
0
0.00995
0.00996
0.00997
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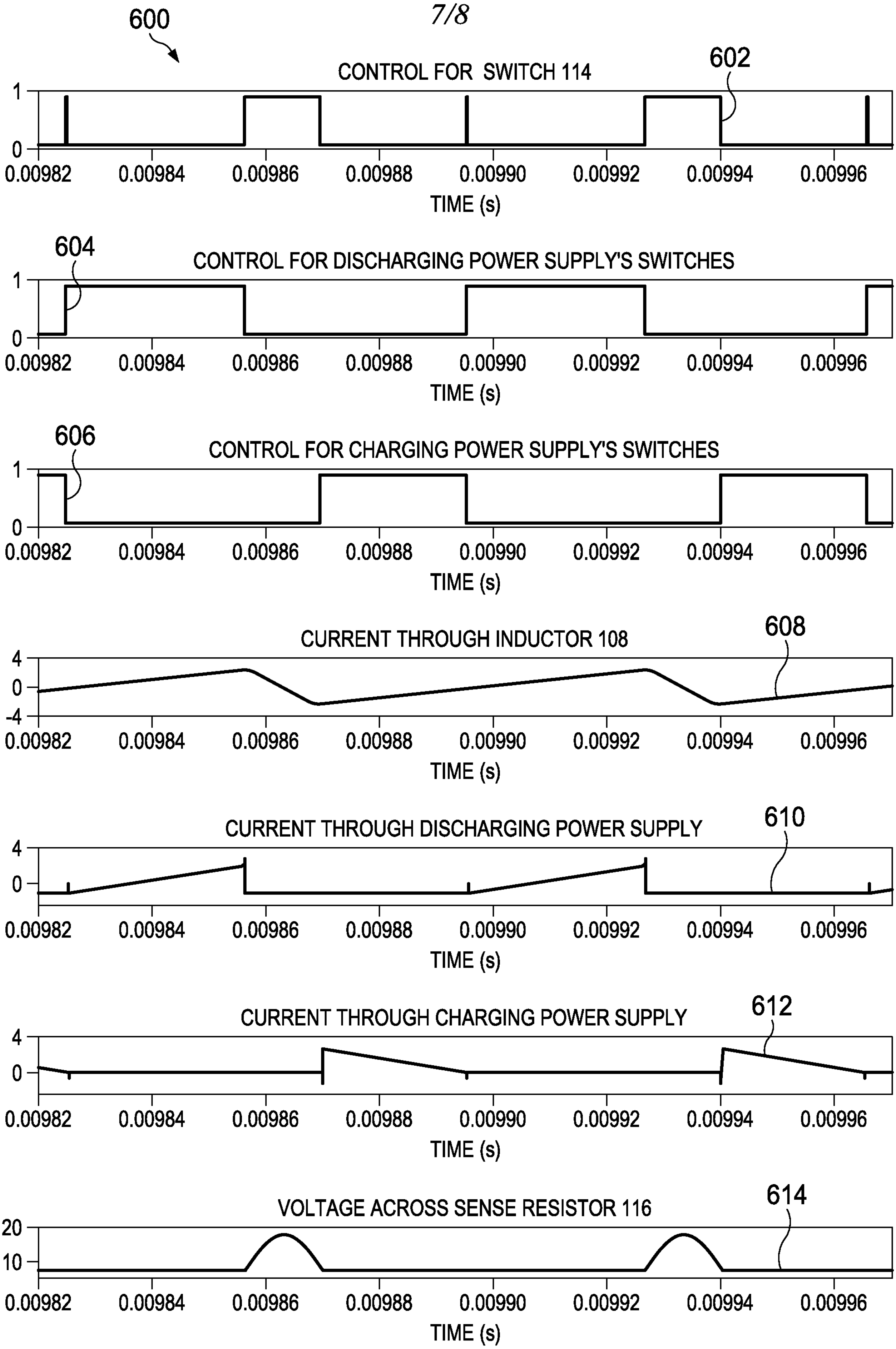
0.00999
TIME (s)

FIG. 5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CONTROL FOR SWITCH 114
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0.00984
0.00986
0.00988
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0.00992
0.00994
0.00996
TIME (s)
604
CONTROL FOR DISCHARGING POWER SUPPLY'S SWITCHES
606
CONTROL FOR CHARGING POWER SUPPLY'S SWITCHES
CURRENT THROUGH INDUCTOR 108
608
4
-4
CURRENT THROUGH DISCHARGING POWER SUPPLY
610
CURRENT THROUGH CHARGING POWER SUPPLY
612
VOLTAGE ACROSS SENSE RESISTOR 116
614
20
10

FIG. 6

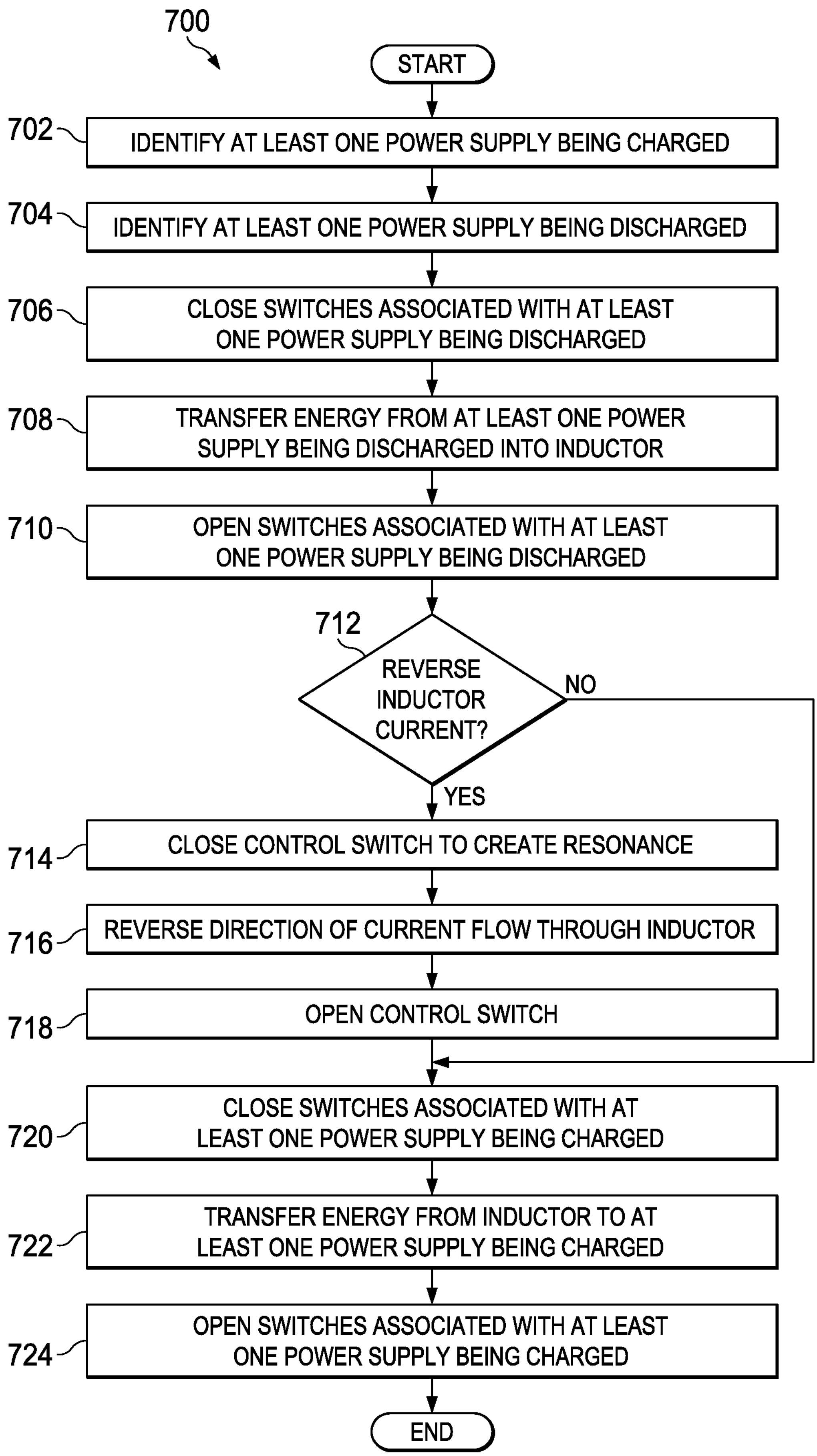
700
START
702
IDENTIFY AT LEAST ONE POWER SUPPLY BEING CHARGED
704
IDENTIFY AT LEAST ONE POWER SUPPLY BEING DISCHARGED
706
CLOSE SWITCHES ASSOCIATED WITH AT LEAST ONE POWER SUPPLY BEING DISCHARGED
708
TRANSFER ENERGY FROM AT LEAST ONE POWER SUPPLY BEING DISCHARGED INTO INDUCTOR
710
OPEN SWITCHES ASSOCIATED WITH AT LEAST ONE POWER SUPPLY BEING DISCHARGED
712
REVERSE INDUCTOR CURRENT?
NO
YES
714
CLOSE CONTROL SWITCH TO CREATE RESONANCE
716
REVERSE DIRECTION OF CURRENT FLOW THROUGH INDUCTOR
718
OPEN CONTROL SWITCH
720
CLOSE SWITCHES ASSOCIATED WITH AT LEAST ONE POWER SUPPLY BEING CHARGED
722
TRANSFER ENERGY FROM INDUCTOR TO AT LEAST ONE POWER SUPPLY BEING CHARGED
724
OPEN SWITCHES ASSOCIATED WITH AT LEAST ONE POWER SUPPLY BEING CHARGED
END

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2012/060023

A. CLASSIFICATION OF SUBJECT MATTER

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

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)
H02J 7/04; H02M 3/335; H03K 5/00; H02J 3/14; H02J 7/00; H02J 7/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: resonance, power, inductor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2009-0096516 A1 (NAKASHIMA HIDENARI) 16 April 2009 see abstract, paragraphs [0035]-[0037], [0041] and figures 2-3.	1-6,10-19 7-9,20
Y A	KR 10-2010-0126235 A (INTERSIL AMERICAS INC.) 01 December 2010 See abstract, paragraphs [0024], [0029] and figure 9.	1-6,10-19 7-9,20
A	US 2002-0075700 A1 (TAKASHI BIRUMACHI) 20 June 2002 See claim 3 and figures 1-2.	1-20
A	US 7817446 B2 (ENDO NAOTO et al.) 19 October 2010 See abstract and figures 1-2.	1-20
A	US 2009-0189448 A1 (VERSCHUEREN ALWIN ROGIER MARTIJN) 30 July 2009 See abstract, claims 1-4 and figures 2-4.	1-20

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
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"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 MARCH 2013 (21.03.2013)	**22 MARCH 2013 (22.03.2013)**

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LEE, Chang Yong
Telephone No. 82-42-481-5398

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2012/060023

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		WO 2008-007298 A3	17.01.2008