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(54) BATTERY MANAGEMENT SYSTEM WITH ADIABATIC SWITCHED-CAPACITOR CIRCUIT

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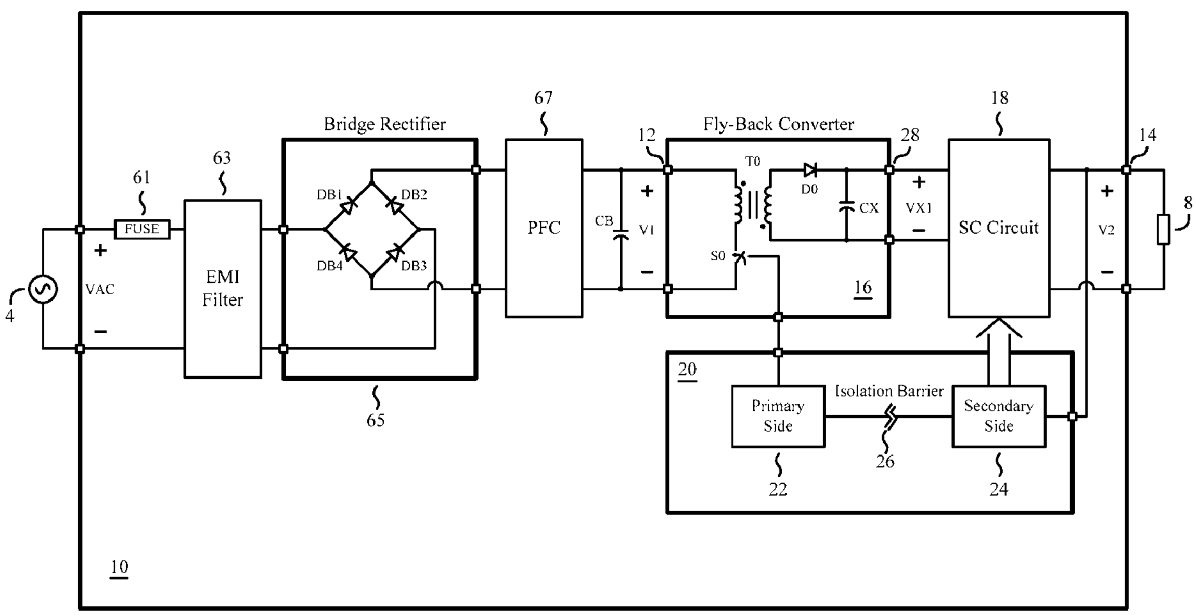
(57) **ABSTRACT**

An apparatus for switching between powering a load from a battery and powering the load from another power source includes a battery manager and a switched-capacitor network, wherein the switched-capacitor network comprises a plurality of capacitors, first and second switch sets, and a controller, wherein the controller causes the switched-capacitor network to transition between a first state and a second state.



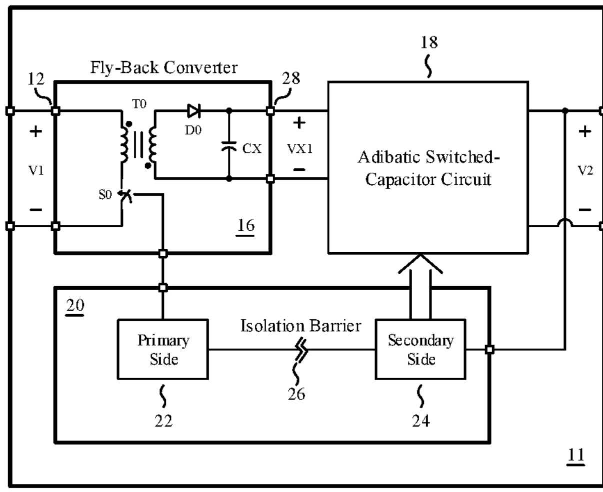

18
Fly-Back Converter
12
28
14
T0
D0
CX
+
VX1
−
Adibatic Switched-Capacitor Circuit
+
V1
−
+
V2
−
S0
16
20
Primary Side
Isolation Barrier
Secondary Side
26
22
24
11

FIG. 1

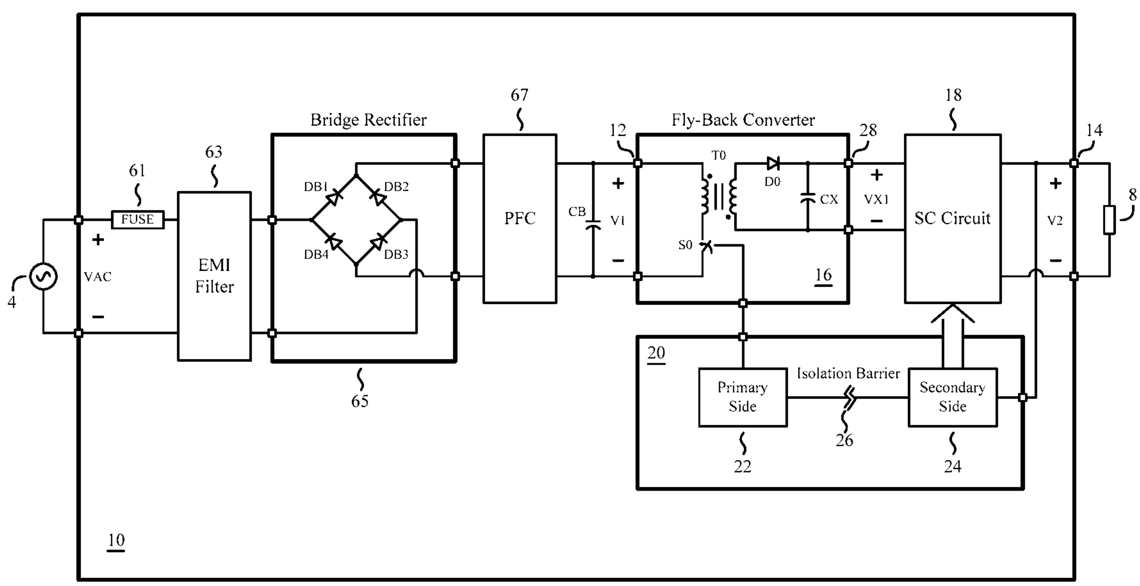

67
18
Bridge Rectifier
12
Fly-Back Converter
28
14
61
63
DB1
DB2
DB4
DB3
FUSE
+
VAC
−
EMI Filter
PFC
CB
V1
T0
D0
CX
VX1
SC Circuit
V2
8
4
S0
16
65
20
Primary Side
Isolation Barrier
Secondary Side
26
22
24
10

FIG. 2

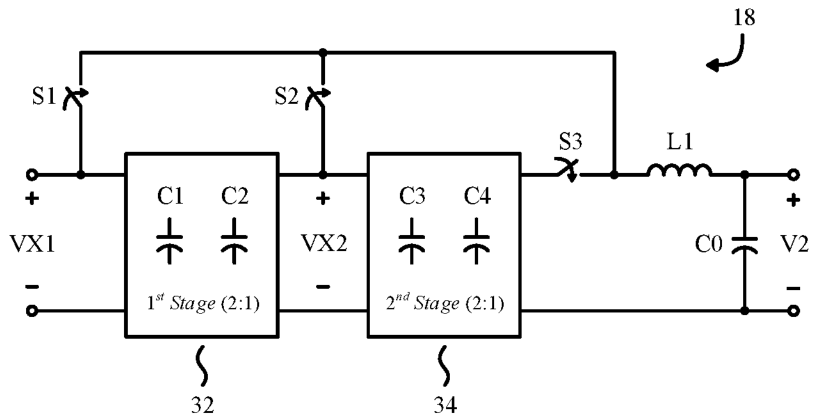

18
S1
S2
S3
L1
C1
C2
C3
C4
VX1
VX2
C0
V2
1st Stage (2:1)
2nd Stage (2:1)
32
34

FIG. 3

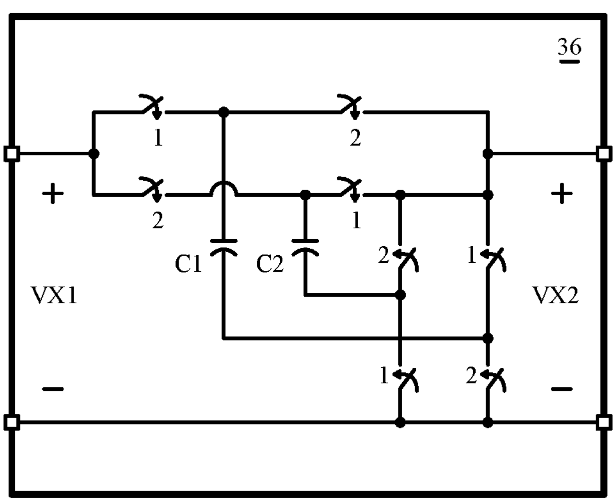

36
1
2
2
1
C1
C2
2
1
1
2
VX1
VX2
+
+
−
−

FIG. 4

Item	Total Value	Comp. Size (W x L x H)	Quantity
L1	120 nH	4.00 x 4.00 x 1.20 mm^3	1
C0	40 μF	1.60 x 0.80 x 1.00 mm^3	8
C1	10 μF	2.00 x 1.25 x 1.25 mm^3	2
C2	10 μF	2.00 x 1.25 x 1.25 mm^3	2
C3	10 μF	2.00 x 1.25 x 1.25 mm^3	1
C4	10 μF	2.00 x 1.25 x 1.25 mm^3	1

FIG. 5

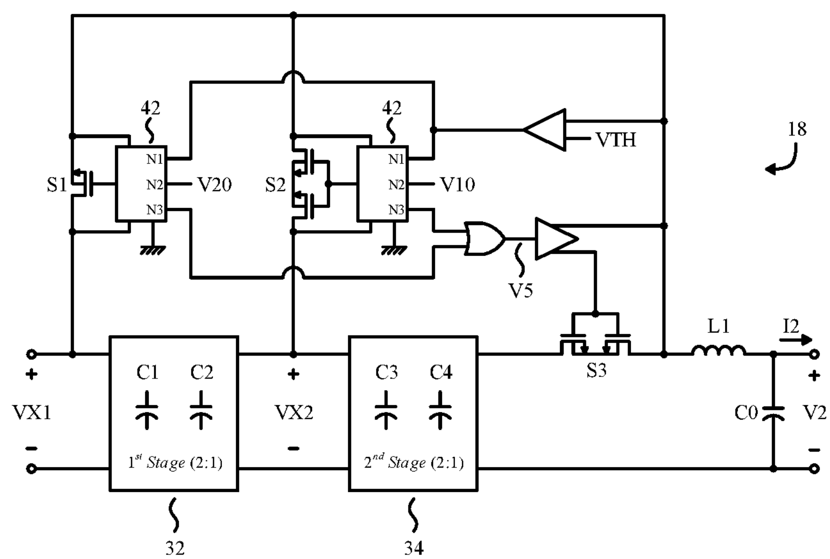


FIG. 6

V2	S1	S2	S3	1st Stage	2nd Stage
5 V	OFF	OFF	ON	ON	ON
10 V	OFF	ON	OFF	ON	OFF
20 V	ON	OFF	OFF	OFF	OFF

FIG. 7

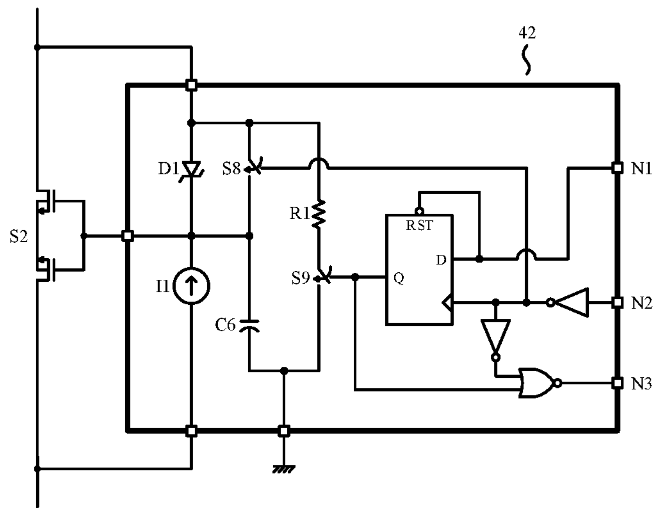


FIG. 8

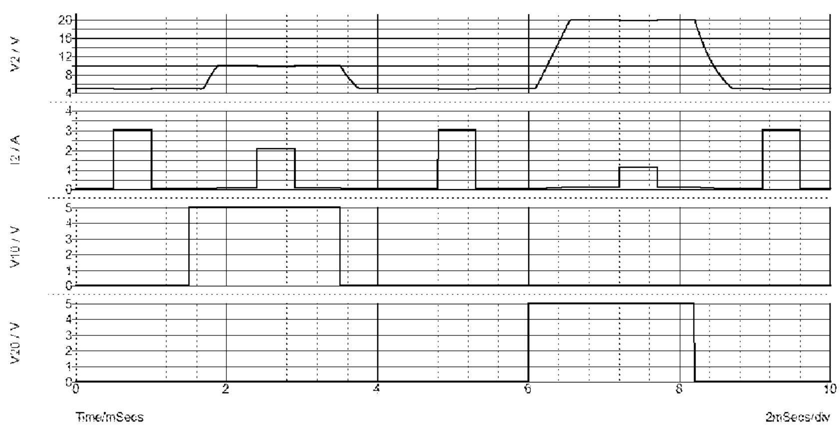


FIG. 9

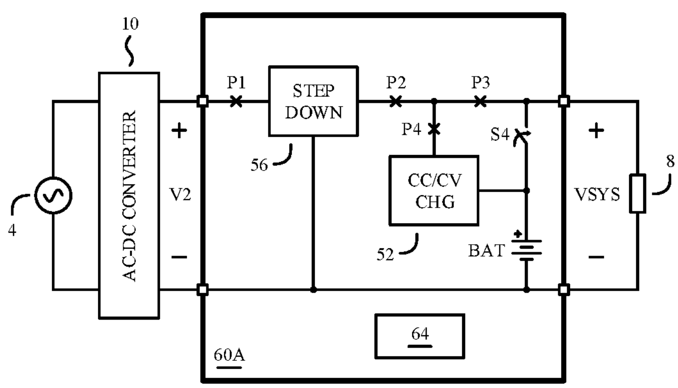


FIG. 10

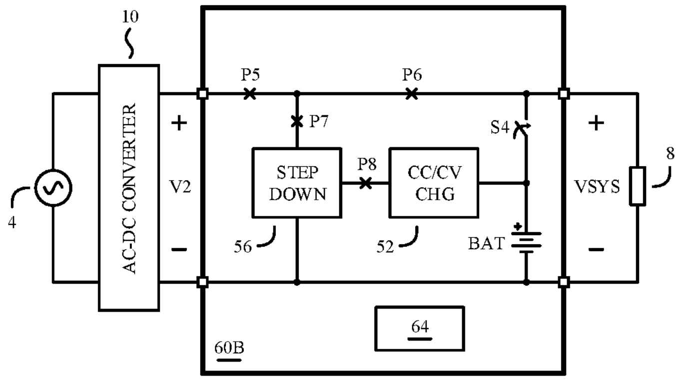


FIG. 11

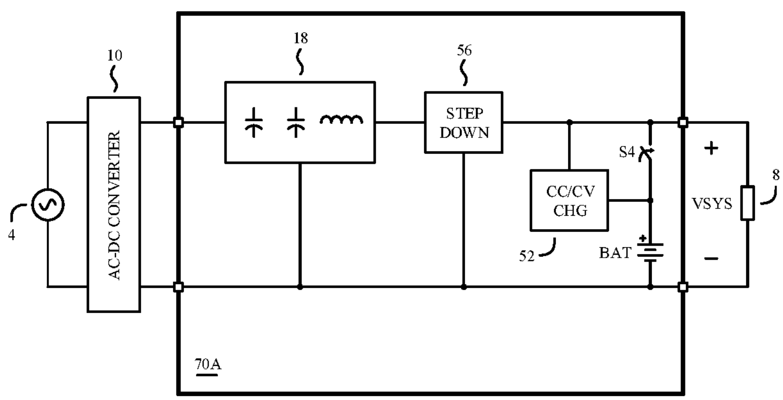


FIG. 12

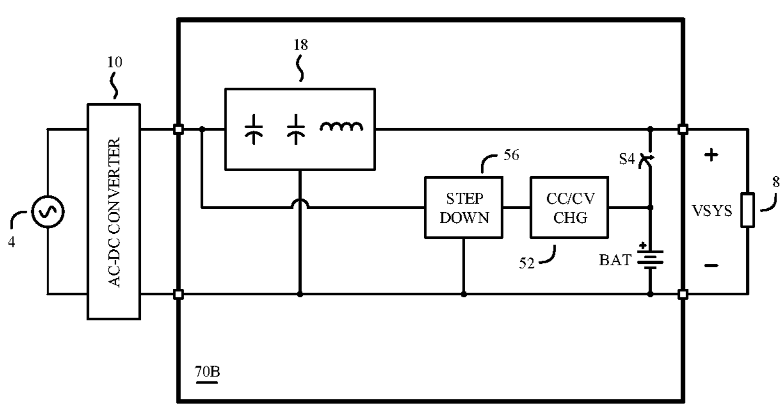


FIG. 13

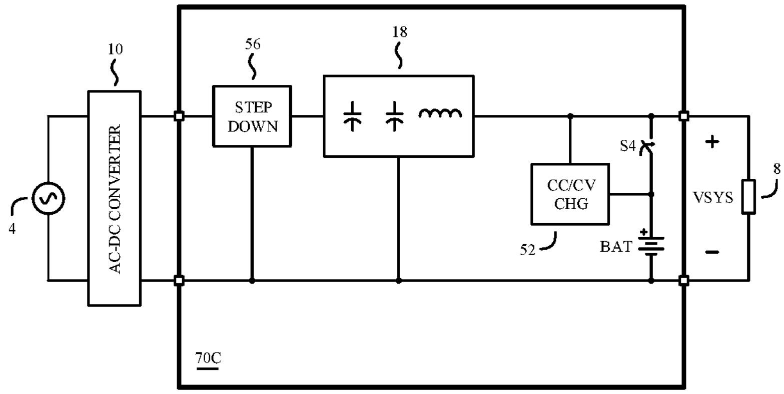


FIG. 14

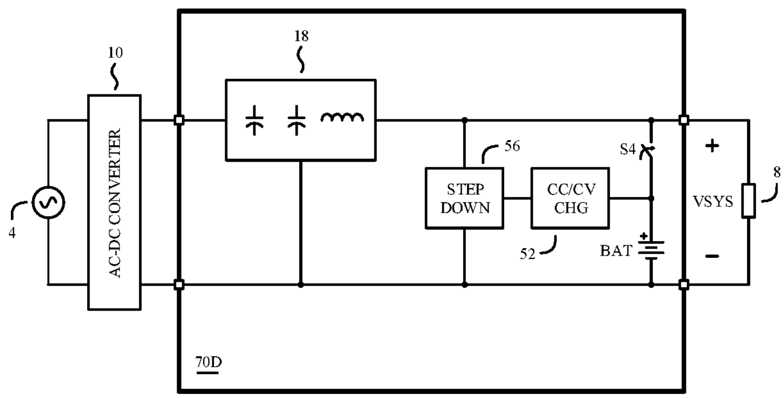


FIG. 15

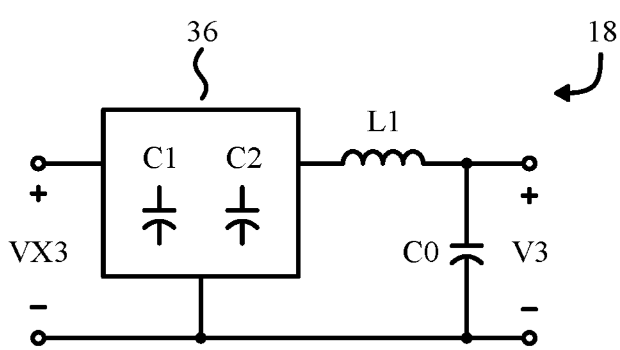


FIG. 16

Item	Required Total Value	Comp. Size (W x L x H)	Total Area
L1	30 nH	4.00 x 4.00 x 1.20 mm^3	1 x 16.00 mm^2
C1	10 µF	2.00 x 1.25 x 1.25 mm^3	2 x 2.50 mm^2
C2	10 µF	2.00 x 1.25 x 1.25 mm^3	2 x 2.50 mm^2
C0	15 µF	2.00 x 1.25 x 1.25 mm^3	3 x 2.50 mm^2

FIG. 17

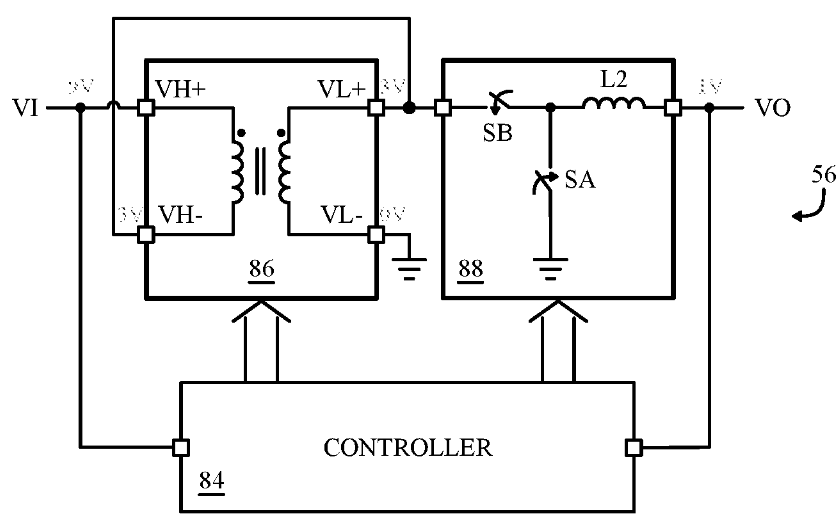


FIG. 18

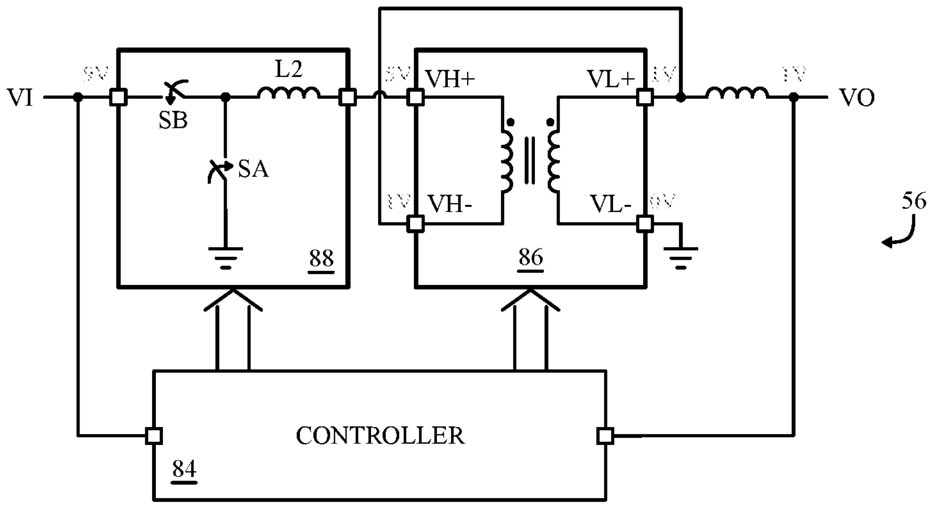

VI
SB
L2
SA
88
VH+
VH-
86
VL+
VL-
VO
56
CONTROLLER
84

FIG. 19

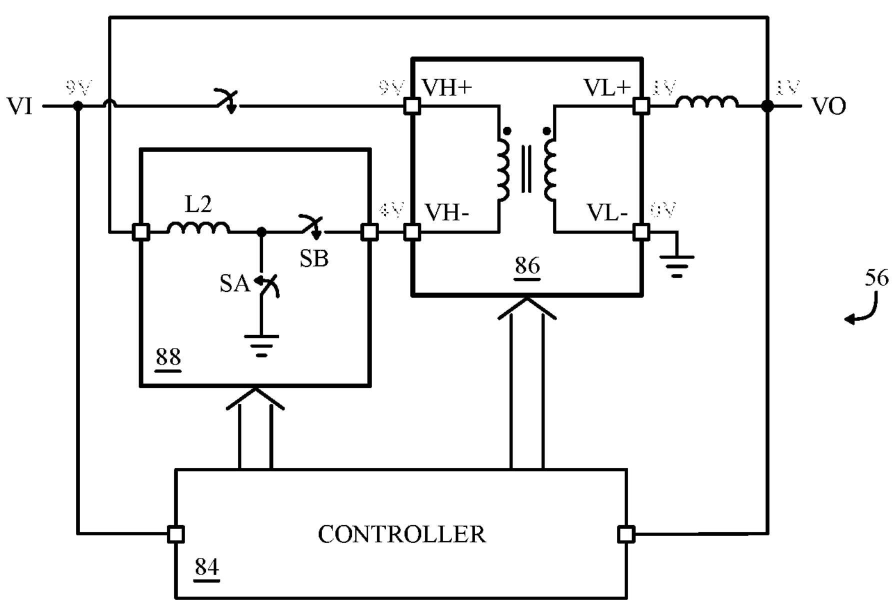

VI
L2
SB
SA
88
VH+
VH-
86
VL+
VL-
VO
56
CONTROLLER
84

FIG. 20

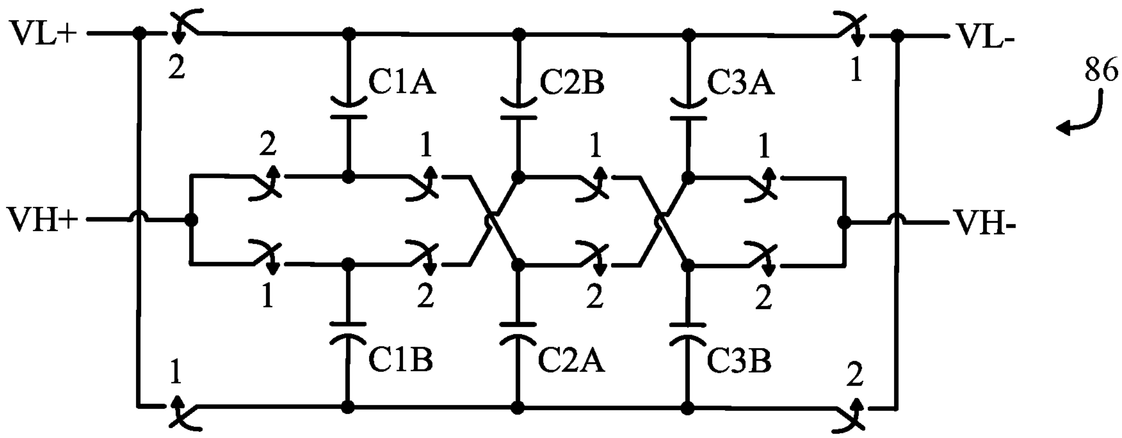

VL+
VL-
VH+
VH-
C1A
C2B
C3A
C1B
C2A
C3B
1
2
86

FIG. 21

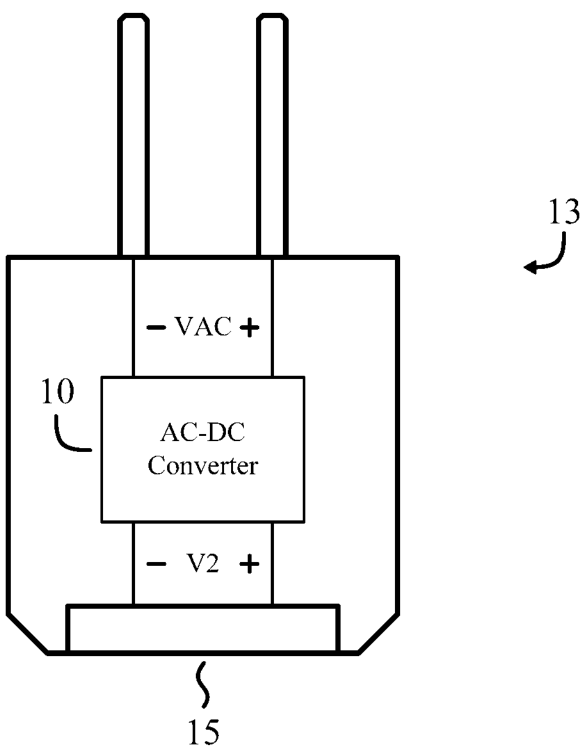

13
VAC
10
AC-DC
Converter
V2
15

FIG. 22

BATTERY MANAGEMENT SYSTEM WITH ADIABATIC SWITCHED-CAPACITOR CIRCUIT

RELATED APPLICATIONS

[0001] This application claims the benefit of the Mar. 11, 2016 priority date of U.S. Provisional Application 62/306,749, the contents of which are herein incorporated by reference.

FIELD OF INVENTION

[0002] This invention relates to power conversion, and in particular, to battery-managers that use switched-capacitors.

BACKGROUND

[0003] Many portable electrical devices are used while the device is plugged into an AC source. During this time, a battery manager must provide power to both charge the battery, if necessary, and to operate the device itself. When the AC source is disconnected, the battery manager must switch over so that the battery provides power to the device.

SUMMARY

[0004] In one aspect, the invention features an apparatus for switching between powering a load from a battery and powering the load from an AC source. Such an apparatus includes a battery manager with an AC/DC converter connected to its input. Either the AC/DC converter or the battery manager includes an adiabatic switched-capacitor network. Such a network is characterized by having a capacitor with charge stored thereon circuitry for constraining a rate of change of the charge at least in part as a result of causing charge to pass through an inductance.

[0005] In another aspect, the invention features an apparatus for switching between powering a load using energy stored in a battery and powering the load using energy from an AC source, the apparatus comprising a battery manager, a switched-capacitor network, a battery charger for charging the battery while the load is being powered using energy from the AC source, and a first controller, wherein the battery manager comprises an input terminal for coupling to a bridge rectifier, wherein the switched-capacitor network comprises a plurality of capacitors and first and second switch sets, wherein closing switches in the first switch set and opening switches in the second switch set arranges the capacitors into a first state, wherein closing the switches in the second set and opening the switches in the first set arranges the capacitors in a second state, and wherein, in operation, the controller causes the switched-capacitor network to transition between the first state and the second state at a specific frequency, thereby transferring charge between capacitors and terminals of the switched-capacitor network.

[0006] In some embodiments, the switched-capacitor network is in the AC/DC converter. Among these are embodiments in which the switched-capacitor network includes a controller, a charge pump, and a switching regulator connected to the charge pump and to a bridge rectifier. In these embodiments, the controller controls the switching regulator and the charge pump.

[0007] In other embodiments, the AC/DC converter is part of the battery manager. There are a variety of locations in which one can place the switched-capacitor network within a battery manager.

[0008] In one of these embodiments, the battery manager comprises an input connected to the AC/DC converter, and a step-down converter. In these embodiments, the switched-capacitor network is between the step-down converter and the input.

[0009] In another of these embodiments, the battery manager comprises, in addition to a step-down converter, an input connected to the AC/DC converter, an output connected to a load, a first line that connects the input to the output, a second line that connects the step-down converter to the first line at a first node, a third line that connects the switch to the first line at a second node, and a switch that selectively connects and disconnects the battery from the first line. In these embodiments, the switched-capacitor network is on the first line between the first and second nodes.

[0010] In another of these embodiments, the battery manager includes, in addition to a step-down converter and a battery charger, a first line extending between the step-down converter and an output to which a load to be driven is to be connected, and a second line that connects the battery charger to the first line at a first node. In these embodiments, the switched-capacitor network is disposed between the first node and the step-down converter.

[0011] In another of these embodiments, the battery manager includes, in addition to a step-down converter, a first line that extends from battery manager's input to its output, and a second line that connects the step-down converter to the first line at a node. In these embodiments, switched-capacitor network is disposed between the battery manager's input and the node.

[0012] In another of these embodiments, the battery step-down converter has an inductance upon the switched-capacitor network relies to limit a rate of change of charge present on a capacitor within the switched-capacitor network.

[0013] Further embodiments include those in which the switched-capacitor network comprises a charge pump, a switching regulator connected to the charge pump, and a controller that controls the switching regulator and the charge pump so as to achieve operation thereof.

[0014] In any of the foregoing embodiments, it is possible for the switched-capacitor network to include a charge pump and an inductance coupled to the charge pump. Among these are embodiments in which the charge pump comprises a cascade multiplier.

[0015] In another aspect, the invention features an apparatus for switching between powering a load from a battery and powering it load from a DC source. Such an apparatus includes a battery manager having an switched capacitor network that includes a capacitor having an amount of charge stored thereon, and circuitry for constrains a rate at which the amount of charge is changed at least in part as a result of causing charge to pass through an inductance.

[0016] Among these embodiments are those in which the battery manager includes an input, and a step-down converter with the switched-capacitor network between them.

[0017] Also among these embodiments are those in which the battery manager includes an input, an output, a first line, a second line, a third line, a step-down converter, and a switch. In these embodiments, the output is configured to be connected to a load that is to be driven, the input is connected to a DC source, the switch selectively connects and disconnects the battery from the first line, the first line connects the input to the output, the second line connects the step-down converter to the first line at a first node, wherein the third line connects the switch to the first line at a second node, and the switched-capacitor network is on the first line between the first and second nodes.

[0018] In yet other embodiments, the battery manager includes a first line, a second line, an output to which a load to be driven is to be connected, a battery charger, and a step-down converter. In these embodiments, the first line extends between the step-down converter and the output, the second line connects the battery charger to the first line at a first node, and the switched-capacitor network is disposed between the first node and the step-down converter.

[0019] In some embodiments, the battery manager comprises the battery charger and a step-down converter. Among these are embodiments in which the step-down converter is disposed such that, in operation, energy for charging the battery and energy for powering the load both pass through the step-down converter, and other embodiments in which it is instead disposed such that, in operation, energy for charging the battery passes through the step-down converter and energy for powering the load bypasses the step-down converter.

[0020] Also among the embodiments are those that include a bypass switch control circuit to control slew rate of voltage transitions in the switched-capacitor circuit.

[0021] In still other embodiments, the battery manager includes an input, an output, a step-down converter, a first line, and a second line. In such embodiments, the first line extends from the input to the output, the second line connects the step-down converter to the first line at a node, and the switched-capacitor network is disposed between the input and the node.

[0022] Still other embodiments are those in which the battery manager includes a step-down converter. In these embodiments, the step-down converter includes an inductance, and the switched-capacitor network relies on the inductance of the step-down converter to limit a rate of change of charge present on a capacitor within the switched-capacitor network.

[0023] Yet other embodiments include a travel charger, with the battery manager being a constituent thereof.

[0024] Among any of the foregoing embodiments are those in which the switched-capacitor network includes a charge pump and an inductance coupled to the charge pump. These include embodiments in which the charge pump includes a cascade multiplier. Also among the foregoing embodiments are those in which the switched-capacitor network is adiabatic and those in which it is diabatic.

[0025] These and other features of the invention will be apparent from the following detailed description and the accompanying figures, in which:

BRIEF DESCRIPTION OF THE FIGURES

[0026] FIG. **1** shows a two-stage power conversion circuit;

[0027] FIG. **2** shows the circuit of FIG. **1** with additional circuitry for receiving an AC voltage;

[0028] FIG. **3** shows a first embodiment of a switched-capacitor architecture for use in the power-conversion circuits of FIGS. **1** and **2**;

[0029] FIG. **4** shows a switching circuit contained in the stages of the power conversion circuit of FIG. **3**;

[0030] FIG. **5** is a parts list for the embodiment shown in FIG. **3**;

[0031] FIG. **6** is a variant of the switched-capacitor architecture of FIG. **3** with circuitry for controlling slew rate;

[0032] FIG. **7** shows operation of switches shown in FIG. **5** for controlling slew rate;

[0033] FIG. **8** shows details of a slew-rate control circuit from the switched-capacitor architecture shown in FIG. **6**;

[0034] FIG. **9** shows slew control carried out by the slew-rate control circuitry shown in FIG. **6**;

[0035] FIG. **10** shows several locations for incorporation of an adiabatic switched-capacitor circuit into a first embodiment of a battery manager;

[0036] FIG. **11** shows several locations for incorporation of an adiabatic switched-capacitor circuit into a second embodiment of a battery manager;

[0037] FIG. **12-15** show battery managers with an adiabatic switched-capacitor circuit at four of the locations shown in FIGS. **10-11**;

[0038] FIG. **16** is a functional block diagram of a typical adiabatic switched-capacitor circuit;

[0039] FIG. **17** shows exemplary components for implementing an adiabatic switched-capacitor circuit;

[0040] FIGS. **18-20** show an implementation of the step-down converter of FIGS. **10-11** that includes an adiabatically charged switched-capacitor network;

[0041] FIG. **21** is a cascade multiplier for use as a switched-capacitor network in the embodiments of FIGS. **18-20**; and

[0042] FIG. **22** shows the circuit of FIG. **2** incorporated into a travel adapter.

DETAILED DESCRIPTION

[0043] Before describing several exemplary embodiments of power converter circuits and processing performed by and on such power converter circuits, it should be appreciated that, in effort to promote clarity in explaining the concepts, reference is sometimes made herein to specific switched-capacitor circuits or specific switched-capacitor circuit topologies. It should be understood that such references are merely exemplary and should not be construed as limiting.

[0044] As used herein, ac-dc converters are the same as AC/DC converters; and switched-capacitor circuits are the same as switched-capacitor networks and charge pumps.

[0045] FIG. **1** shows a two-stage power conversion circuit **11** having a first terminal **12** that connects to a first stage and a second terminal **14** that connects to a second stage. The first terminal **12** is at a first voltage V**1** and the second terminal **14** is at a second voltage V**2**.

[0046] In the illustrated embodiment, the first stage is implemented as a switch-mode pre-regulator **16** and the second stage is implemented as an adiabatic switched-capacitor circuit **18**. However, in alternative embodiments, this second stage is non-adiabatic, or diabatic.

[0047] The pre-regulator **16** can be implemented in a variety of ways, so long as the essential function thereof, namely regulation of an output voltage, can be carried out. In the illustrated embodiment, the pre-regulator **16** includes a pre-regulator switch S**0**, a transformer T**0**, a diode D**0**, and a filter capacitor CX. A particularly useful implementation of a pre-regulator **16** is a magnetically-isolated converter, an example of which is a fly-back converter.

[0048] A variety of fly-back converters can be used to implement the pre-regulator **16**. These include a quasiresonant fly-back converter, an active-clamp fly-back converter, an interleaved fly-back converter, and a two-switch fly-back converter.

[0049] Other examples of magnetically-isolated converters are forward converters. Examples of suitable forward converters include a multi-resonant forward converter, an active-clamp forward converter, an interleaved forward converter, and a two-switch forward converter.

[0050] Yet other examples of magnetically-isolated converters are half-bridge converters and full-bridge converters. Examples of half-bridge converters include an asymmetric half-bridge converter, a multi-resonant half-bridge converter, and an LLC resonant half-bridge converter. Examples of full-bridge converters include an asymmetric full-bridge converter, a multi-resonant full-bridge converter, and an LLC resonant full-bridge converter.

[0051] It is also possible to implement the pre-regulator **16** using a non-isolated converter. Examples include a buck converter, a boost converter, and a buck-boost converter.

[0052] As used herein, two functional components are said to be "isolated," or more specifically, "galvanically isolated," if energy can be communicated between those components without a direct electrical conduction path between those components. Such isolation thus presupposes the use of another intermediary for communicating energy between the two components without having actual electrical current flowing between them. In some cases, this energy may include information.

[0053] Examples include the use of a wave, such as an electromagnetic, mechanical, or acoustic wave. As used herein, electromagnetic waves include waves that are in span the visible range, the ultraviolet range, and the infrared range. Such isolation can also be mediated through the use of quasi-static electric or magnetic fields, capacitively, inductively, or mechanically.

[0054] Most functional components have circuitry in which different parts of the circuit are at different electrical potentials. However, there is always a potential that represents the lowest potential in that circuit. This is often referred to as "ground" for that circuit.

[0055] When a first and second functional component are connected together, there is no guarantee that the electrical potential that defines ground for the first component will be the same as the electrical potential that defines ground for the second circuit. If this is the case, and if these components are connected together, it will be quite possible for electrical current to flow from the higher of the two grounds to the lower of the two grounds. This condition, which is called a "ground loop," is undesirable. It is particularly undesirable if one of the two components happens to be a human being. In such cases, the current in the ground loop may cause injury.

[0056] Such ground loops can be discouraged by galvanically isolating the two components. Such isolation essentially forecloses the occurrence of ground loops and reduces the likelihood that current will reach ground through some unintended path, such as a person's body.

[0057] The switched-capacitor circuit **18** can be implemented as a switched-capacitor network. Examples of such networks include ladder networks, Dickson networks, Series-Parallel networks, Fibonacci networks, and Doubler networks. These can all be adiabatically charged and configured into multi-phase networks. A particularly useful switched-capacitor network is an adiabatically charged version of a full-wave cascade multiplier. However, diabatically charged versions can also be used.

[0058] As used herein, changing the charge on a capacitor "adiabatically" means causing an amount of charge stored in that capacitor to change by passing the charge through a non-capacitive element. A positive adiabatic change in charge on the capacitor is considered adiabatic charging while a negative adiabatic change in charge on the capacitor is considered adiabatic discharging. Examples of non-capacitive elements include inductors, magnetic elements, resistors, and combinations thereof. In either case, the result is a constraint on the rate at which the quantity of charge on the capacitor can change.

[0059] In some cases, a capacitor can be charged adiabatically for part of the time and diabatically for the rest of the time. Such capacitors are considered to be adiabatically charged. Similarly, in some cases, a capacitor can be discharged adiabatically for part of the time and diabatically for the rest of the time. Such capacitors are considered to be adiabatically discharged.

[0060] Diabatic charging includes all charging that is not adiabatic and diabatic discharging includes all discharging that is not adiabatic.

[0061] As used herein, an "adiabatic switched-capacitor circuit" is a network having at least one capacitor that is both adiabatically charged and adiabatically discharged. A "diabatic switched-capacitor circuit" is a network that is not an adiabatic switched-capacitor circuit.

[0062] Examples of pre-regulators **16**, switched-capacitor circuits **18**, their accompanying circuitry, and packaging techniques can be found U.S. Pat. Nos. 9,362,826, 9,497,854, 8,723,491, 8,503,203, 8,693,224, 9,502,968, 8,619,445, 9,203,299, and 9,041,459, U.S. Patent Publications 2016/0197552, 2015/0102798, 2014/0301057, 2013/0154600, 2015/0311786, 2014/0327479, 2016/0028302, 2014/0266132, 2015/0077175, and 2015/0077176, and PCT publications WO2014//062279, WO2015//138378, WO2015//138547, WO2016//149063, and WO 2017/007991, the contents of which are herein incorporated by reference.

[0063] Adiabatic switched-capacitor circuits are described in detail in U.S. Pat. No. 8,860,396, issued Oct. 14, 2014, in U.S. Provisional Applications 62/132,701 and 62/132,934, both of which were filed on Mar. 13, 2015. The contents of the foregoing documents are incorporated herein by reference.

[0064] A first controller **20** controls the operation of the first and second stages. The first controller **20** includes a primary side **22** that controls the first stage and a secondary side **24** that controls the second stage. An isolation barrier **26** separates the primary side **22** from the secondary side **24**.

[0065] The primary side **22** of the first controller **20** controls the pre-regulator switch S**0**. Opening and closing the pre-regulator switch S**0** controls the current provided to a primary side of the transformer T**0**. This, in turn, controls the voltage across the filter capacitor CX. When the pre-regulator switch S**0** is on, the diode D**0** is off and when the pre-regulator switch S**0** is off, the diode D**0** is on.

[0066] The pre-regulator **16** also includes a regulator-output terminal **28** maintained at an intermediate voltage VX**1** that is lower than the first voltage V**1**. This regulator-output terminal **28** connects to the adiabatic switched-capacitor circuit **18**. The adiabatic switched-capacitor circuit **18** thus receives this intermediate voltage VX**1** and transforms it into the second voltage V**2**.

[0067] The adiabatic switched-capacitor circuit **18** operates in discrete steps. Thus, it only provides coarse regulation of its output. It cannot provide fine regulation of its output. It is for the pre-regulator **16** to carry out this fine regulation. The two-stage design shown in FIG. **1** reduces the need for the pre-regulator **16** to sustain a high-current burden. This means that the secondary winding of the transformer T**0** can instead carry a much smaller RMS current. This, in turn, lowers winding loss and reduces the voltage ripple at the regulator-output terminal **28**. It also means that the filter capacitor CX that couples the pre-regulator **16** to the adiabatic switched-capacitor circuit **18** can be made smaller.

[0068] However, the improved performance of the pre-regulator **16** cannot be completely offset by the increased size and power loss of having the adiabatic switched-capacitor circuit **18** in the second stage. Therefore, it is imperative that the adiabatic switched-capacitor circuit **18** be both extremely efficient and small.

[0069] The two-stage power conversion circuit **11** in FIG. **1** is shown as being configured to receive a DC voltage. In an alternative embodiment shown in FIG. **2**, a bridge rectifier **65** coupled to the first terminal **12** by a coupling capacitor CB provides a way to receive an AC voltage VAC.

[0070] The power conversion circuit **10** of FIG. **2** is similar to that shown in FIG. **1**, but with additional circuitry for receiving an AC voltage VAC provided by an AC source **4** and converting that AC voltage VAC into the second voltage V**2**. The AC voltage VAC is provided to input terminals of a bridge rectifier **65** having bridge diodes DB**1**, DB**2**, DB**3**, and DB**4** arranged to form a bridge and having an output across a bridge capacitor CB. The output across the bridge capacitor CB becomes the first voltage V**1** presented at the first terminal **12**. A power-conversion circuit **10** of this type may be incorporated into a travel adapter **13**, as shown in FIG. **22**. Such a travel adapter **13** outputs a DC voltage at a USB port **15**.

[0071] Some embodiment include circuitry for controlling harmonic current and thus boosting the ratio of real power to apparent power that flows through the power supply. This is particularly useful for power supplies that attach to a wall outlet that supplies an AC voltage. An example of such circuitry is an active power-factor corrector **67** disposed between the bridge rectifier **65** and the pre-regulator **16**.

[0072] FIG. **2** also shows a fuse **61** between the AC power source **4** and the remaining components of the power-conversion circuit **10** for safety. An electromagnetic interference filter **63** is also provided to suppress the uncontrolled emission of electromagnetic waves that may arise during operation of the power-conversion circuit **10**.

[0073] FIG. **3** shows a first embodiment of a switched-capacitor circuit **18** that is designed to accept a nominal voltage of 20 volts and to produce a variety of output voltages, such as 5 volts and 10 volts. This is particularly useful for Type-C travel adapters. This is because, unlike the older USB standards, in which the output is always five volts, the newer USB Type C standard permits higher output voltages, such as ten, fifteen, and even twenty volts.

[0074] FIG. **3** shows a first embodiment of an adiabatic switched-capacitor circuit **18** that is designed to accept a nominal voltage of 20 volts. The illustrated adiabatic switched-capacitor circuit **18** features a first switched-capacitor stage **32**, a second switched-capacitor stage **34**, a first bypass switch S**1**, a second bypass switch S**2**, and a third bypass switch S**3**. An LC filter having an output inductor L**1** and an output capacitor C**0** permit adiabatic operation. By selectively opening and closing the bypass switches S**1**, S**2**, S**3**, it is possible to selectively bypass selected ones of the first and second switched-capacitor stages **32**, **34**.

[0075] Each of the first and second stages **32**, **34** is a 2× voltage divider having a maximum voltage conversion from VX**1** to VX**2** of 4:1. The resulting adiabatic switched-capacitor circuit **18** is designed to accept an intermediate voltage VX**1** of 20 volts and to provide a voltage of either 20 volts, 10 volts, or 5 volts. Some embodiments deliver a 15-volt output voltage, which is sometimes required by the Type-C standard. This can be provided by having the pre-regulator **16** deliver 15 volts to the switched-capacitor circuit **18** instead of 20 volts and running the switched-capacitor circuit **18** in the 1:1 mode.

[0076] The adiabatic switched-capacitor circuit **18** shown in FIG. **3** has three modes of operation, a 1:1 mode, a 2:1 mode, and a 4:1 mode. In the 1:1 mode, the first bypass switch S**1** closes, and the second and third bypass switches S**2** and S**3** open. In the 2:1 mode, the second bypass switch S**2** closes and the first and third bypass switches S**1** and S**3** open. In the 4:1 mode, the third bypass switch S**3** closes and the first and second bypass switches S**1** and S**2** open. All bypassed stages run in a low-power mode to save power since they are not needed to provide voltage conversion (i.e., they are not switching at a specific frequency).

[0077] FIG. **4** illustrates a switched-capacitor circuit **36** inside the first stage **32**. A similar circuit is within the second stage **34**. During operation, this circuit transitions between first and second states. In the first state, all switches labeled "**1**" close and all switches labeled "**2**" open. In the second state, all switches labeled "**1**" open and all switches labeled "**2**" close. The switched-capacitor circuit **36** alternates between the first and second state at a specific frequency. This frequency is one that is selected to produce a second intermediate voltage VX**2** that is half of the intermediate voltage VX**1**.

[0078] FIG. **5** shows a component list for one implementation of the adiabatic switched-capacitor circuit **18** shown in FIG. **3**. The components were selected so the solution provides a high efficiency, a small solution size, and a maximum output voltage ripple of 100 mV peak-to-peak. The total value column specifies the total amount of inductance and/or capacitance required of the components at their operating condition.

[0079] In an alternative embodiment, the first and second bypass switches S**1**, S**2** can be turned on and off in such a way that the second voltage V**2** slews up and down in a controlled manner. This is particularly useful when there is a maximum slew rate to be met. For example, in the case of a Type-C USB power adapter, where the second voltage V**2** is programmable from 5 volts to 20 volts, there is a maximum slew-rate requirement of 30 mV/μs for voltage transitions.

[0080] FIG. **6** shows an alternative embodiment of the adiabatic switched-capacitor circuit **18** of FIG. **3** in which first and second bypass switch control circuits **42** are added to control the slew rate of voltage transitions in the adiabatic switched-capacitor circuit **18** shown in FIG. **3**. These bypass switch control circuits **42** control the slew rate of voltage transitions in the adiabatic switched-capacitor circuit **18** shown in FIG. **3** when the output transitions from 5 volts to 10 volts and from 5 volts to 20 volts. The bypass switch control circuit **42** also controls the second voltage V**2** slew-rate from 10 volts to 5 volts and 20 volts to 5 volts.

[0081] FIG. **7** shows a table of bypass switch states for three different voltage outputs.

[0082] Referring to FIG. **6**, to output 20 volts, one asserts a first control input V**20**. To output only 10 volts, one asserts a second control input V**10**. By default, when neither the first nor the second output is asserted, the adiabatic switched-capacitor circuit **18** outputs 5 volts.

[0083] FIG. **8** shows details of a bypass switch control circuit **42** shown in FIG. **6**. Although the second bypass switch S**2** is shown in FIG. **8**, the first bypass switch S**1** is controlled in a similar way. All of the bypass switches S**1**, S**2**, and S**3** are N-channel FETs (NFETs). The composite back-to-back NFET configuration for the second and third bypass switches S**2**, S**3** is necessary to block the flow of reverse current from the output to the input when these switches are off while the first bypass switch S**1** is on. Although the second and third bypass switches S**2**, S**3** are depicted as discrete back-to-back NFETs in FIG. **8**, these devices may be replaced by a single transistor with an adaptive body switch in a fully integrated solution.

[0084] A first slew-control switch S**8** in FIG. **8** turns off the first and second bypass switches S**1**, S**2** by shorting their gate and source terminals. When either the first bypass switch S**1** or the second bypass switch S**2** is turned on, the first slew-control switch S**8** (in the respective control) circuit opens, and the second voltage V**2** transitions from 5 volts to 10 volts or from 5 volts to 20 volts. Meanwhile, an anti-slewing capacitor C**6** and a constant current source I**1** control the upward slew rate of the second voltage V**2** transition from 5 volts to 10 volts or 20 volts.

[0085] When the first and second bypass switches S**1**, S**2** are turned off and the second voltage V**2** transitions from 10 volts to 5 volts or 20 volts to 5 volts, a second slew-control switch S**9** turns on and allows a bleeder resistor R**1** to discharge the anti-slewing capacitor C**6**. This controls the downward slew rate of the second voltage V**2**.

[0086] A comparator in FIG. **6** detects when the second voltage V**2** has dropped below a certain threshold VTH (e.g., VTH=5.25 V) and terminates the discharge of the anti-slewing capacitor C**6** by opening the second slew-control switch S**9**. Note that the bleeder resistor R**1** may be replaced by a current source, and the slew rates of both positive and negative voltage transitions may be programmed by making the current source I**1**, the bleeder resistor R**1**, and the anti-slewing capacitor C**6** be programmable or re-configurable.

[0087] When 20 volts is desired at the output, the second and third bypass switches S**2**, S**3** are off while the first bypass switch S**1** is on. The first and second (2:1) switched-capacitor stages are also off. The first bypass switch S**1** is an N-channel FET (NFET) whose turn-on is controlled by the current source I**1**, which is a constant current source, and the anti-slewing capacitor C**6** such that the second voltage V**2** slews up at a fixed rate.

[0088] During the 5-volt to 20-volt transition, the first and second slew-control switches S**8**, S**9** are open and the first bypass switch S**1** acts as a source-follower. In this configuration, the voltage on the source of the first bypass switch S**1** follows the voltage on its gate, which is given by the current though the current source I**1** divided by the capacitance of the anti-slewing capacitor C**6**. Initially, when the first bypass switch S**1** turns on and the second voltage V**2** slews up, the first bypass switch S**1** operates in the saturation region (i.e., $V_{DS}>V_{GS}-V_T$, where V_T is the NFET's threshold voltage). As the output approaches its final level, the first bypass switch S**1** transitions into the linear region and acts as a low-impedance switch. A Zener diode D**1** clamps the gate-to-source voltage (V_{GS1}) of the bypass switch S**1** to a safe level (e.g., V_{GS1} equals 5 volts) during steady-state operation. The transition from 20 volts back to 5 volts is controlled by the bleeder resistor R**1**, which discharges the output capacitance in a slew-rate controlled manner.

[0089] When 10 volts is desired at the output, the first and third bypass switches S**1**, S**3** are off while the second bypass switch S**2** is on. The first (2:1) switched-capacitor stage is on and the second switched-capacitor stage is off. The second bypass switch S**2** includes back-to-back NFETs, that operate as a source follower when the second voltage V**2** transitions from 5 volts to 10 volts. As described previously, the current source I**1** and anti-slewing capacitor C**6** control the slew rate of the second voltage V**2** as it transitions from 5 volts to 10 volts, the bleeder resistor R**1** controls the transition from 10 volts back to 5 volts, and the Zener diode D**1** clamps the gate-to-source voltage of the second bypass switch S**2** to a safe level during steady-state operation at 10 volts (i.e. V**2**).

[0090] Although not explicitly shown in FIGS. **6** and **8**, it should be understood by those skilled in the art that additional circuitry is useful to protect the system against various single-point failures and fault conditions such as over-current, over-temperature, and over-voltage on any and all nodes, switches, and passive components.

[0091] FIG. **9** shows typical voltage transitions for the switched-capacitor circuit with slew-rate limited bypass switch control in a Type-C USB power adapter. The second voltage V**2** slews up and down at approximately 20 mV/μs. According to the USB PD specification, the load must be in a low-power standby state during voltage transitions. For the simulation results shown in FIG. **9**, the load was turned on after the output settled to its final level.

[0092] FIG. **10** illustrates a first battery manager **60**A that provides energy to power to a load **8** while also providing energy for charging a battery BAT using power delivered from an ac-dc converter **10** connected to an AC source **4**. The first battery manager **60**A supplies a system voltage VSYS for powering the load **8**. It does so even when the ac-dc converter **10** is disconnected from the battery manager **60**A.

[0093] The AC source **4** need not be a wall-source. Instead, the AC source **4** can be part of a wireless charging system for charging the device. Such a wireless charging system typically includes a base station and a device to be charged. The base station receives AC at a first frequency and provides it to a frequency-converter that steps it up to a higher frequency and provides it to a first coil. The device to be charged includes a second coil selected such that, when brought in proximity with the first coil, the two form an air-core transformer. This permits energy provided by the first coil to be made available at the second coil so that it can be used to charge the battery on the device to be charged.

[0094] The conversion to a higher frequency is useful for ensuring that the first coil can be made a reasonable size. Typical output frequencies are in the range of 50 kHz. Various standards exist for the extent of the frequency transition and the amount of voltage and/or current provided by the base station. An example of such a standard is the QI standard.

[0095] The first battery manager **60**A includes a step-down converter **56** that transforms a second voltage V**2** provided by the ac-dc converter **10** into the system voltage VSYS. It also includes a constant-current/constant voltage (CCCV) charger **52** that provides power for charging the battery BAT. The charger **52** includes circuitry for maintaining either a constant current or a constant voltage while charging of the battery, for measuring the amount of charge on the battery, and for providing protection from faults. The step-down converter **56** can either be a part of a device powered by the battery or it can be placed outside such a device. A battery switch S**4** selectively connects and disconnects the battery BAT from the load **8**. A second controller **64** synchronizes operation of the step-down converter **56** and the charger **52**.

[0096] When the ac-dc converter **10** connects to an AC source **4**, the battery BAT is not needed for supplying power to the load **8**. Accordingly, the second controller **64** opens the battery switch S**4**. Meanwhile, the step-down converter **56** lowers the second voltage V**2** to a value a little above the charging voltage of the battery BAT, thereby allowing the CC/CV charger **52** to charge the battery efficiently, assuming the battery is not already fully charged. The step-down converter **56** also provides the necessary system voltage VSYS to the load **8**.

[0097] However, once the ac-dc converter **10** is disconnected, the step-down converter **56** can no longer supply power. The second controller **64** therefore closes the battery switch S**4** so that the battery BAT can supply the necessary system voltage VSYS.

[0098] FIG. **11** illustrate a second battery manager **60**B, where the charging voltage and system voltage VSYS are separated, unlike in the first battery manager **60**A. The battery switch S**4** is only closed when the battery is used as a source of power for the system voltage VSYS. The advantage of this second battery manager **60**B over the first battery manager **60**A is that the step-down converter **56** does not have to supply power to charge the battery BAT and the system voltage VSYS when the ac-dc converter **10** is connected.

[0099] In some embodiments, the ac-dc converter **10** includes an adiabatically charged switched-capacitor converter of the type illustrated in FIGS. **2-4** and variants thereof.

[0100] FIGS. **10** and **11** collectively show first through eighth locations P**1**, P**2** . . . P**8** in which an adiabatic switched-capacitor circuit **18** of the type shown in FIG. **3** can be placed within the first and second battery managers **60**A, **60**B. More than one adiabatic switched-capacitor circuit **18** can actually be used, however, the largest performance improvement will likely be seen by only incorporating a single adiabatic switched-capacitor circuit **18**.

[0101] FIG. **12** shows a third battery manager **70**A in which the adiabatic switched-capacitor circuit **18** is placed at the first location P**1**. Incorporating an adiabatic switched-capacitor circuit **18** into the third battery manager **70**A reduces the burden on the step-down converter **56**. For example, in the third battery manager **70**A, shown in FIG. **12**, the voltage stress is about half of what it would have been had the adiabatic switched-capacitor circuit **18** been omitted. This has the effect of drastically reducing the power loss in the step-down converter **56** for a given output power.

[0102] FIG. **13** shows a fourth battery manager **70**B in which the adiabatic switched-capacitor circuit **18** is instead placed at the sixth location P**6**. Placement of the adiabatic switched-capacitor circuit **18** provides a way to target the part of the circuit in which improvement is sought. For example, in the fourth battery manager **70**B, shown in FIG. **13**, the main improvement is not in the step-down converter **56**, but in the downstream point-of-load (POL) converters in a load **8**.

[0103] The configurations shown in FIGS. **12** and **13** are particularly useful because they are most compatible with existing integrated circuits that implement battery managers.

[0104] FIG. **14** shows a fifth battery manager **70**C in which the adiabatic switched-capacitor circuit **18** has been placed in the second position P**2**. FIG. **15** shows a sixth battery manager **70**D in which the adiabatic switched-capacitor circuit **18** has been placed in the fifth position P**5**.

[0105] FIG. **16** shows a block diagram of a typical adiabatic switched-capacitor circuit **18**. The circuit is a 2× voltage divider that provides a 2:1 voltage conversion from an input voltage VX**3** to an output voltage V**3**. This adiabatic switched-capacitor circuit **18** is designed to accept a maximum input voltage of 24 volts.

[0106] FIG. **17** shows an example component list for the architecture in FIG. **16**.

[0107] A typical step-down converter **56** as shown in FIGS. **10-11** generally includes a switching regulator. Accordingly, some embodiments incorporate a switched-capacitor converter **86** in the step-down converter **56** together with a third controller **84** that controls both the switched-capacitor converter **86** and the built-in switching regulator **88**. The third controller **84** can thus operate the switched-capacitor converter **86**, as shown in FIG. **18**, in such a way that the switching regulator **88** adiabatically charges and discharges the capacitors within the switched-capacitor converter **86**. This provides a way to achieve adiabatic charge and discharge without the need to provide an extra LC filter with the switched-capacitor converter **86**. Additionally, the switched-capacitor converter **86** in this case is inherently modular and can readily be supplied as a separate component to be incorporated in an existing step-down converter **56**.

[0108] FIGS. **19-20** illustrate two additional architectures that implement the same concept. The embodiment shown in FIG. **19** is the reverse of the embodiment in FIG. **18**. While the embodiment shown in FIG. **20**, provides an efficient way to convert power by placing the switching regulator **88** in series with the input of the switched-capacitor converter **86** and in parallel with the output of the switched-capacitor converter **86**. Therefore, the switching regulator **88** only carries a fraction of the current delivered to the output while still retaining the ability to directly control the current delivered to the output.

[0109] The third controller **84** in the embodiments of FIGS. **18-20** provides control signals to turn the switches within the switching regulator **88** and the switched-capacitor converter **86** on and off in response to a sensed output voltage VO and/or input voltage VI. Based on these inputs, the controller **84** makes necessary adjustments to the control signals provided to switching regulator **88** and to the switched-capacitor converter **86** such that the such that the output voltage VO is regulated within some tolerance.

[0110] In the illustrated embodiments, the switching regulator **88** is a Buck converter that includes a first switch SA, a second switch SB, and an inductor L**2**. When the first switch SA is closed, the second switch SB is open, and vice versa. The first and second switches SA, SB operate at a specific frequency. This frequency controls an average dc current through the inductor L**2**. This makes it possible to control the voltage at the output terminal of the inductor L**2** (i.e., the terminal not connected to the switches) by varying the duty cycle of the first switch SA. In particular, the longer the first switch SA is closed during a cycle the lower the voltage at the output terminal of the inductor L**2** will be.

[0111] FIG. **21** illustrates a detailed circuit diagram of one implementation in which the switched-capacitor converter **86** is a full-wave cascade multiplier. The switched-capacitor converter **86** includes a first set **1** of switches, a second set **2** of switches, and capacitors C**1**A-C**3**B. Closing switches in the first switch set **1** and opening switches in the second switch set **2** arranges the capacitors C**1**A-C**3**B are arranged in a first state. Conversely, closing the switches in the second set **2** and opening the switches in the first set **1** arranges the capacitors C**1**A-C**3**B in a second state. During normal operation, the switched-capacitor converter **86** cycles between the first state and the second state at a specific frequency, thereby transferring charge between the capacitors C**1**A-C**3**B and terminals. The switched-capacitor converter **86** can be modeled as a dc transformer as in FIGS. **18-20**. In this implementation, the voltage conversion ratio (VH to VL) is three to one.

[0112] In some implementations, a computer-accessible storage-medium includes a database representative of one or more components of the converter. For example, the database may include data representative of a switching network that has been optimized to promote low-loss operation of a charge pump.

[0113] Generally speaking, a computer-accessible storage-medium may include any non-transitory storage media accessible by a computer during use to provide instructions and/or data to the computer. For example, a computer accessible storage medium may include storage media such as magnetic or optical disks and semiconductor memories.

[0114] Generally, a database representative of the system may be a database or other data structure that can be read by a program and used, directly or indirectly, to fabricate the hardware comprising the system. For example, the database may be a behavioral-level description or register-transfer level (RTL) description of the hardware functionality in a high level design language (HDL) such as Verilog or VHDL. The description may be read by a synthesis tool that may synthesize the description to produce a netlist comprising a list of gates from a synthesis library. The netlist comprises a set of gates that also represent the functionality of the hardware comprising the system. The netlist may then be placed and routed to produce a data set describing geometric shapes to be applied to masks. The masks may then be used in various semiconductor fabrication steps to produce a semiconductor circuit or circuits corresponding to the system. In other examples, Alternatively, the database may itself be the netlist (with or without the synthesis library) or the data set.

Having described the invention, and a preferred embodiment thereof, what is claimed as new, and secured by Letters Patent is:

1-68. (canceled)

69. An apparatus comprising a battery manager, a switching network, a battery charger for charging a battery, and a first controller, wherein said battery manager comprises an input terminal for coupling to an AC/DC converter, wherein said switching network comprises first and second switch sets, wherein said switching network, when connected to a capacitor set that comprises a capacitor, forms a switched-capacitor network, wherein closing switches in said first switch set and opening switches in said second switch set arranges said capacitor set into a first state, wherein closing said switches in said second set and opening said switches in said first set arranges said capacitor set into a second state, and wherein, in operation, said controller causes said switched-capacitor network to transition between said first state and the second state at a specific frequency, thereby transferring charge between said capacitor set and terminals of said switched-capacitor network.

70. The apparatus of claim **69**, wherein said battery manager comprises said switched-capacitor network.

71. The apparatus of claim **69**, wherein said battery manager comprises an input and a step-down converter, wherein said input is connected to said AC/DC converter, and wherein said switched-capacitor network is between said step-down converter and said input.

72. The apparatus of claim **69**, wherein said battery manager comprises a step-down converter connected to said input terminal and to said switched-capacitor network and a switch that selectively connects and disconnects a battery from said switched-capacitor network and from an output terminal of said battery manager.

73. The apparatus of claim **69**, wherein said battery manager comprises a step-down converter connected between said input terminal and said switched-capacitor network and a switch that selectively connects and disconnects said battery from said switched-capacitor network and an output of said battery manager.

74. The apparatus of claim **69**, wherein said switched capacitor-network connects to an input terminal of said battery manager and wherein said battery manager further comprises a step-down converter that connects to said switched-capacitor network and to an output terminal of said battery manager and a switch that selectively connects said battery to said switched-capacitor network and to said output terminal.

75. The apparatus of claim **69**, wherein said battery manager comprises a step-down converter, wherein said step-down converter comprises an inductance, and wherein said switched-capacitor network relies on said inductance of said step-down converter to limit a rate of change of charge present on said capacitor.

76. The apparatus of claim **69**, wherein said AC/DC converter comprises said first controller, a charge pump, and a switching regulator connected to said charge pump, wherein said first controller controls said switching regulator and said charge pump.

77. The apparatus of claim **69**, wherein said switched-capacitor network comprises a charge pump and an inductance coupled to said charge pump.

78. The apparatus of claim **69**, further comprising rate-control circuitry, wherein during operation of said switched-capacitor network, said capacitor has an amount of charge stored thereon, and wherein said rate-control circuitry is configured to constrain a rate at which said amount of charge is changed at least in part as a result of causing charge to pass through an inductance.

79. The apparatus of claim **69**, wherein said battery is configured to receive energy wirelessly from an AC source.

80. The apparatus of claim **69**, wherein said battery charger switches between attempting to maintain a constant current while charge is being provided to said battery and attempting to maintain a constant voltage while charge is being provided to said battery.

81. The apparatus of claim **69**, further comprising a travel charger, wherein said battery manager is a constituent of said travel charger.

82. The apparatus of claim **69**, wherein said battery-charger is a CCCV charger.

83. The apparatus of claim **69**, wherein said controller comprises an isolation barrier between a primary and secondary section thereof.

84. The apparatus of claim **69**, wherein said switched-capacitor network is one that, during operation thereof, causes said capacitor to experience a change in charged stored therein by causing charge to be passed through a non-capacitive element.

85. The apparatus of claim **69**, further comprising a travel adapter, wherein said AC/DC converter is a constituent of said travel adapter, wherein said travel adapter comprises a USB port, and wherein said travel adapter receives an AC voltage and outputs a DC voltage at said USB port.

86. The apparatus of claim **69**, wherein said battery manager comprises said battery charger and a step-down converter, wherein said step-down converter is disposed such that, in operation, energy for charging said battery and energy for powering said load both pass through said step-down converter.

87. The apparatus of claim **69**, wherein said battery manager comprises said battery charger and a step-down converter, wherein said step-down converter is disposed such that, in operation, energy for charging said battery passes through said step-down converter and energy for powering said load bypasses said step-down converter.

88. The apparatus of claim **69**, further comprising a bypass switch control circuit to control slew rate of voltage transitions in said switched-capacitor circuit.

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