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King et al.

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(54) **SWITCHING POWER CONVERTER**

(71) Applicant: **Cirrus Logic International Semiconductor Ltd.**, Edinburgh (GB)

(72) Inventors: **Eric J. King**, Dripping Springs, TX (US); **Siddharth Maru**, Austin, TX (US); **John L. Melanson**, Austin, TX (US)

(73) Assignee: **Cirrus Logic, Inc.**, Austin, TX (US)

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H02M 3/158 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H02M 3/158*** (2013.01); ***H02J 7/34*** (2013.01); ***H02J 7/345*** (2013.01); ***H02M 1/084*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H02M 2001/008; H02M 2001/009; H02M 1/10; H02M 3/158; H02M 3/1582
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,166,527 A 12/2000 Dwelley et al.
6,215,286 B1 4/2001 Scoones et al.
(Continued)

FOREIGN PATENT DOCUMENTS

EP 1804368 A1 7/2007
EP 2571153 A1 3/2013
(Continued)

OTHER PUBLICATIONS

International Search Report and Written Opinion of the International Searching Authority, International Application No. PCT/US2016/061327, dated Feb. 23, 2017.
(Continued)

Primary Examiner — Yusef A Ahmed
Assistant Examiner — David A. Singh
(74) *Attorney, Agent, or Firm* — Jackson Walker L.L.P.

(57) **ABSTRACT**

An apparatus may include a power converter having a power supply input for receiving an input power supply voltage generated by a power supply, an output for generating an output voltage to a load, and a power inductor coupled between the power supply input and the output may and further include an energy storage element coupled to the power supply input, the power inductor, and the output such that operation of the power inductor is split temporally between delivering energy to the energy storage element and delivering energy to the load, and operation of the energy storage element is split temporally between delivering energy to the load and receiving energy from one or both of the power supply and the load.

20 Claims, 5 Drawing Sheets

CONFIGURATION	31	32	33	34	35	36	37	PROPOSED ENERGY TRANSFER/EFFECT
A	1	0	0	1	0	0	0	CHARGE POWER INDUCTOR 42 FROM BATTERY 40
B	1	0	1	0	0	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO LOAD AT OUTPUT OF SMPS 30
C	1	0	0	0	1	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO TO CAPACITOR 44
D	0	0	0	1	0	1	0	CHARGE POWER INDUCTOR 42 FROM CAPACITOR 44
E	0	0	1	0	0	1	0	TRANSFER ENERGY BETWEEN TO LOAD AT OUTPUT OF SMPS 30 AND CAPACITOR 44
F	0	1	1	0	0	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO LOAD AT OUTPUT OF SMPS 30
G	0	1	0	0	1	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO TO CAPACITOR 44
H	0	1	0	1	0	0	0	MAINTAIN INDUCTOR CURRENT
I	0	0	0	1	0	0	1	TRANSFER ENERGY TO POWER INDUCTOR 42 FROM LOAD AT OUTPUT OF SMPS 30
J	0	0	0	0	1	0	1	TRANSFER ENERGY FROM LOAD AT OUTPUT OF SMPS 30 TO CAPACITOR 44

(51) **Int. Cl.**

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H02M 1/084	(2006.01)
H02M 1/10	(2006.01)
H02J 7/34	(2006.01)

(52) **U.S. Cl.**
CPC ***H02M 1/10*** (2013.01); *H02M 1/088* (2013.01); *H02M 3/1582* (2013.01); *H02M 2001/008* (2013.01); *H02M 2001/009* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,348,779	B1	2/2002	Sluijs	
6,348,781	B1	2/2002	Midya et al.	
6,355,990	B1 *	3/2002	Mitchell	H02J 1/06 307/125
2004/0239299	A1	12/2004	Vinciarelli	
2006/0238029	A1 *	10/2006	Hoon	H02M 3/158 307/39
2011/0199062	A1	8/2011	Singnurkar	
2012/0229110	A1 *	9/2012	Huang	H02M 3/1582 323/282
2013/0119966	A1	5/2013	Touzani et al.	
2013/0264870	A1 *	10/2013	Keysar	H02J 1/00 307/24
2014/0232359	A1	8/2014	Dash et al.	
2014/0246908	A1 *	9/2014	Chew	H02M 3/156 307/24
2016/0099582	A1 *	4/2016	Ramorini	H02J 7/0052 320/162
2016/0329830	A1	11/2016	Hussain et al.	
2017/0141675	A1	5/2017	King et al.	

FOREIGN PATENT DOCUMENTS

EP	2835900	A1	2/2015
GB	2484012	A	3/2012
WO	200113502	A1	2/2001
WO	2016179515	A1	11/2016

OTHER PUBLICATIONS

Combined Search and Examination Report under Sections 17 and 18(3), Application No. GB1619079.5, dated Apr. 18, 2017.

* cited by examiner

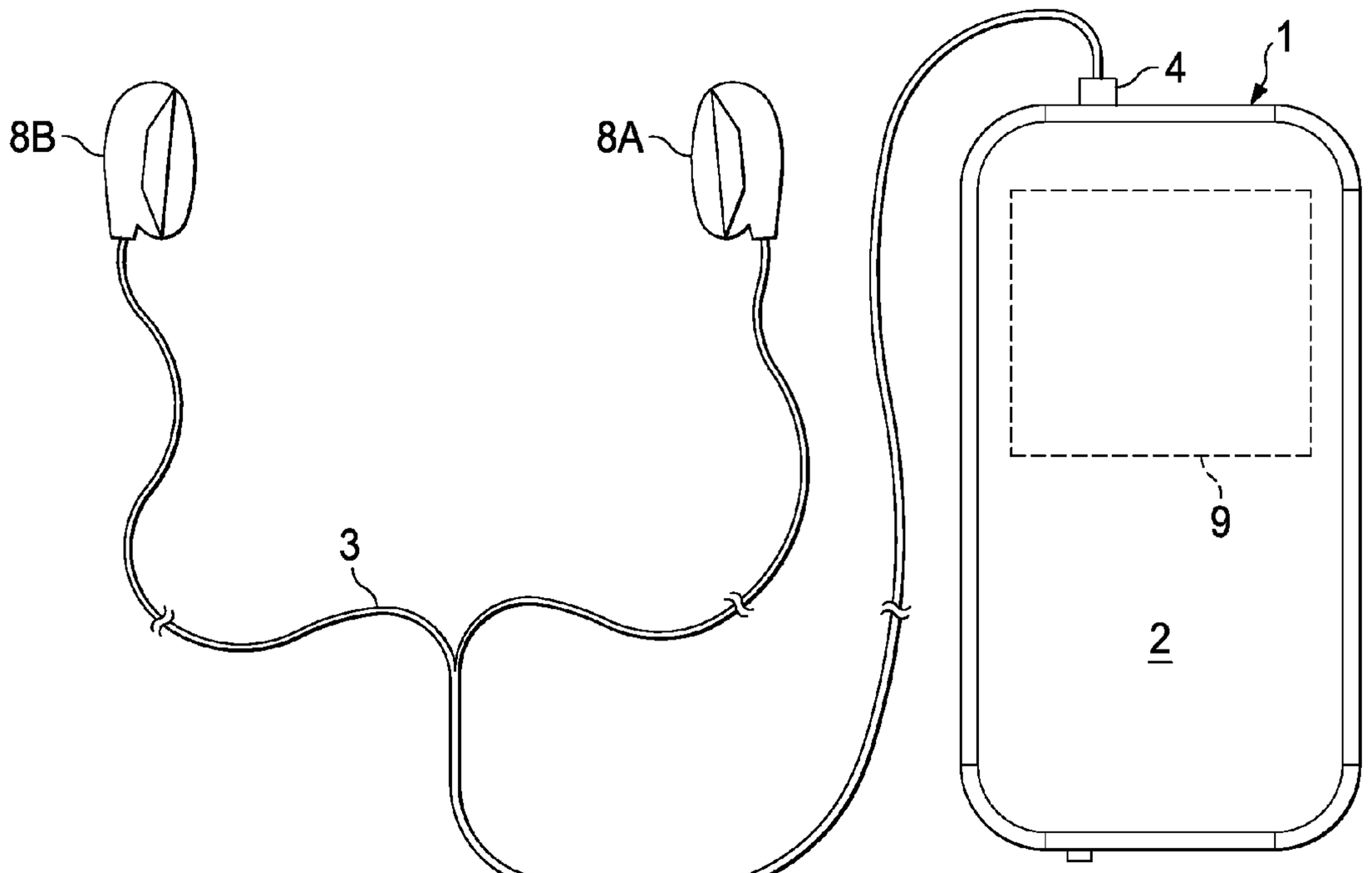

8B
8A
4
1
3
9
2

FIG. 1

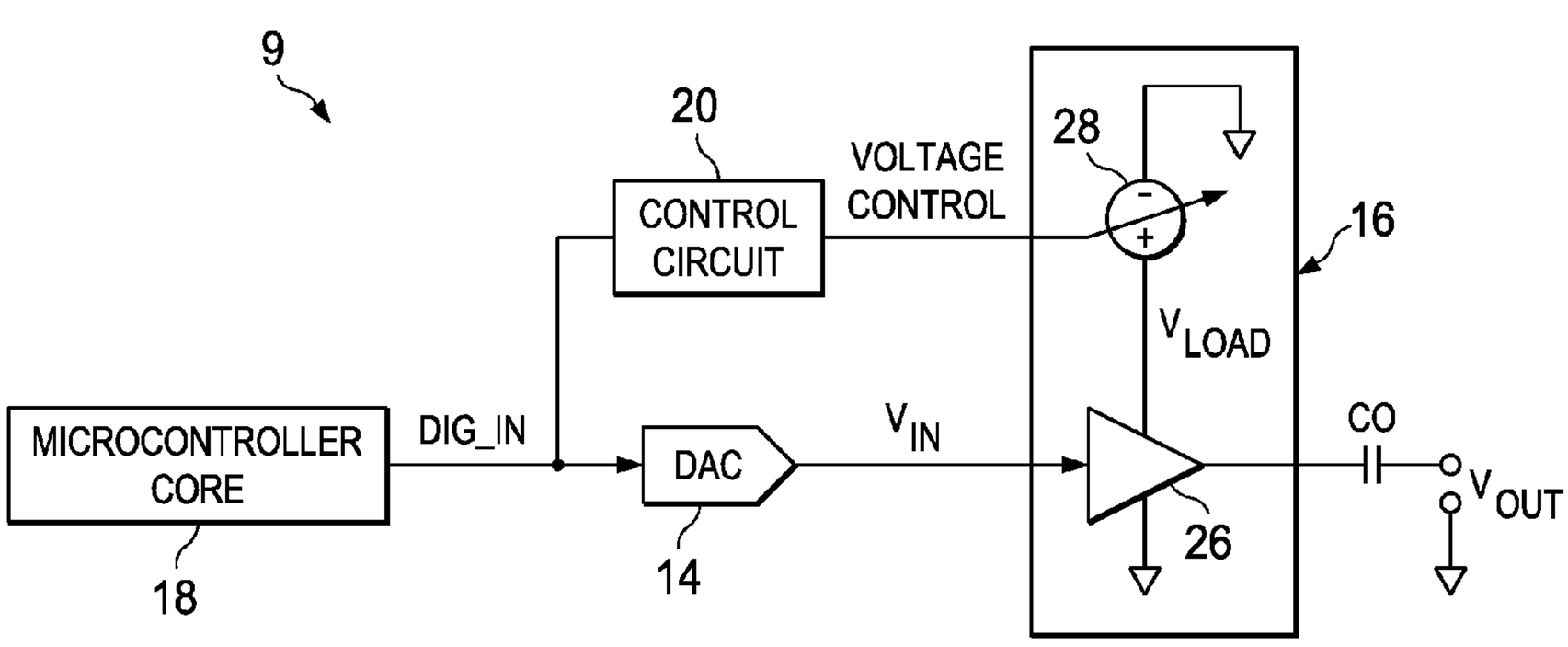

9
20
CONTROL CIRCUIT
VOLTAGE CONTROL
28
16
V_{LOAD}
MICROCONTROLLER CORE
DIG_IN
DAC
V_{IN}
CO
V_{OUT}
18
14
26

FIG. 2

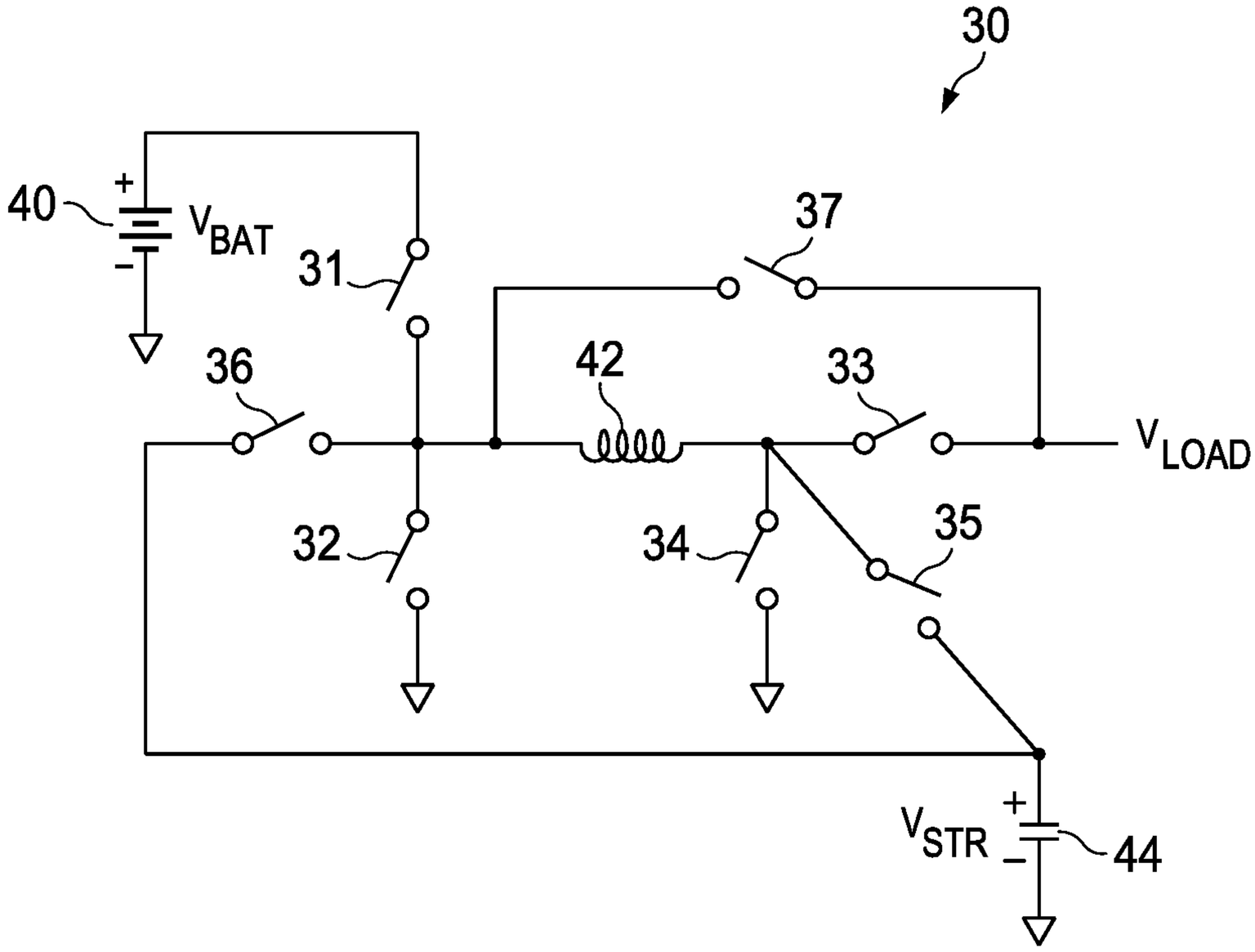


FIG. 3

CONFIGURATION	31	32	33	34	35	36	37	PROPOSED ENERGY TRANSFER/EFFECT
A	1	0	0	1	0	0	0	CHARGE POWER INDUCTOR 42 FROM BATTERY 40
B	1	0	1	0	0	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO LOAD AT OUTPUT OF SMPS 30
C	1	0	0	0	1	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO TO CAPACITOR 44
D	0	0	0	1	0	1	0	CHARGE POWER INDUCTOR 42 FROM CAPACITOR 44
E	0	0	1	0	0	1	0	TRANSFER ENERGY BETWEEN TO LOAD AT OUTPUT OF SMPS 30 AND CAPACITOR 44
F	0	1	1	0	0	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO LOAD AT OUTPUT OF SMPS 30
G	0	1	0	0	1	0	0	TRANSFER ENERGY FROM POWER INDUCTOR 42 TO TO CAPACITOR 44
H	0	1	0	1	0	0	0	MAINTAIN INDUCTOR CURRENT
I	0	0	0	1	0	0	1	TRANSFER ENERGY TO POWER INDUCTOR 42 FROM LOAD AT OUTPUT OF SMPS 30
J	0	0	0	0	1	0	1	TRANSFER ENERGY FROM LOAD AT OUTPUT OF SMPS 30 TO CAPACITOR 44

FIG. 4

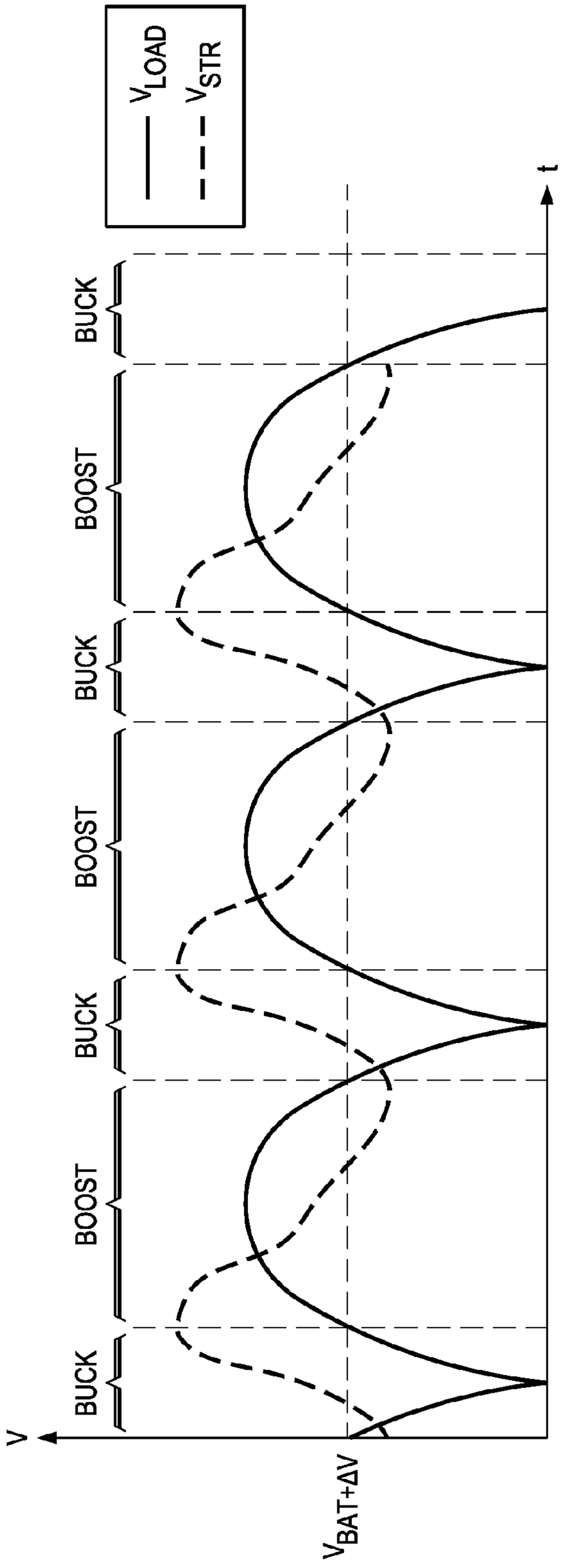

V_{LOAD}
V_{STR}
t
BUCK
BOOST
BUCK
BOOST
BUCK
BOOST
BUCK
V
$V_{BAT+\Delta V}$

FIG. 5

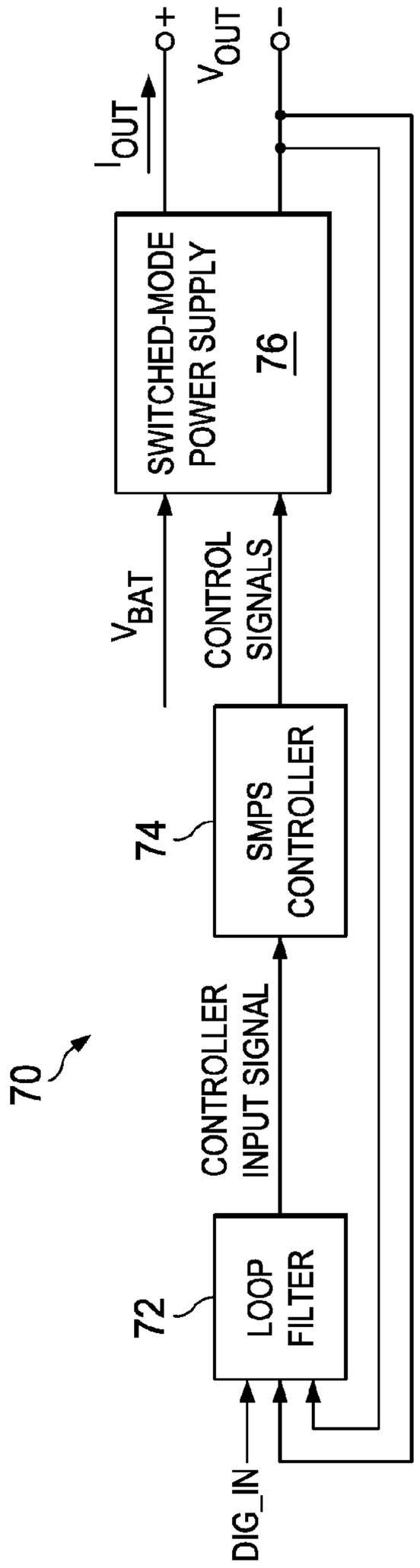

I_{OUT}
o+
V_{OUT}
o−
SWITCHED-MODE POWER SUPPLY
76
V_{BAT}
CONTROL SIGNALS
74
SMPS CONTROLLER
70
CONTROLLER INPUT SIGNAL
72
LOOP FILTER
DIG_IN

FIG. 7

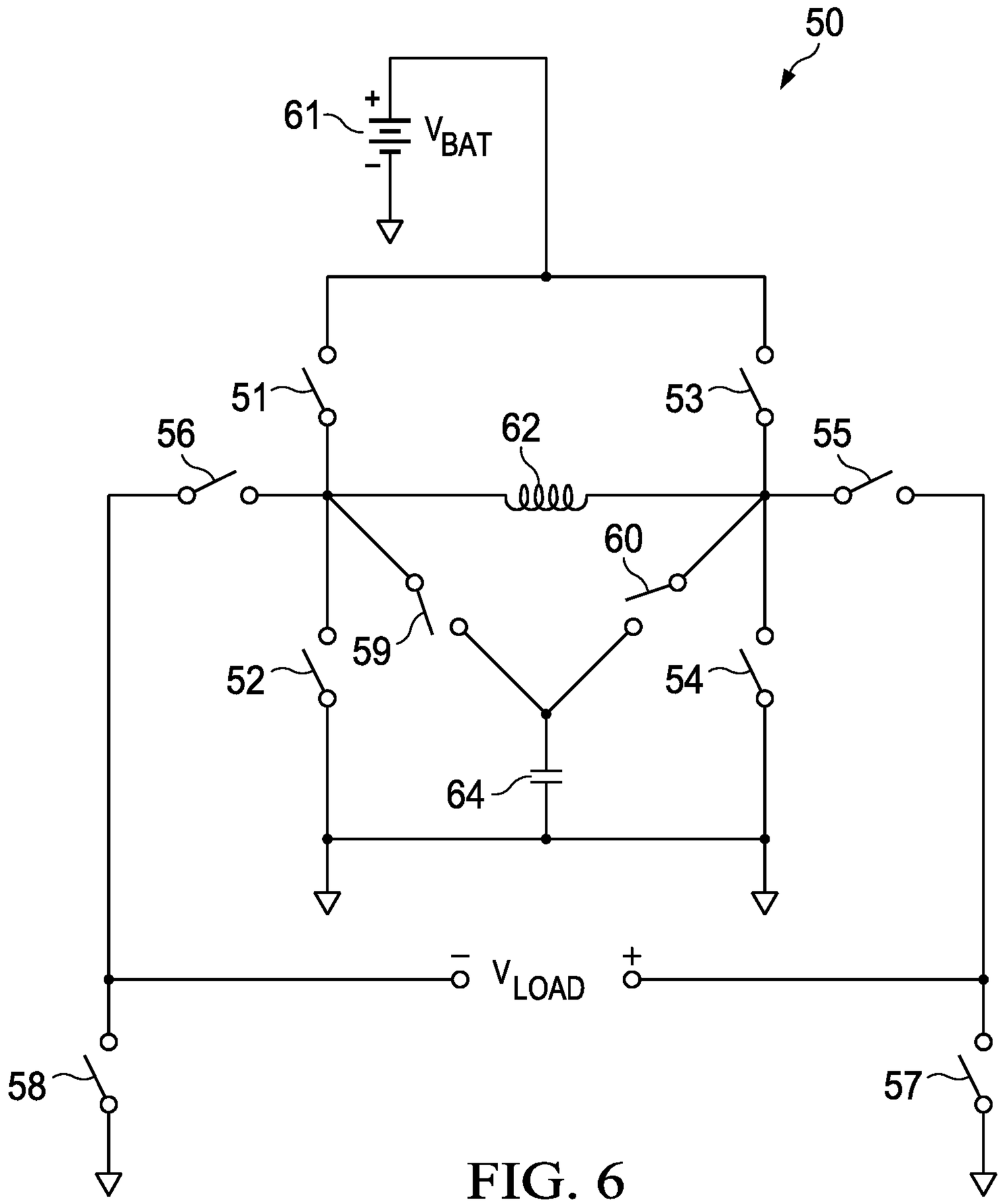


FIG. 6

SWITCHING POWER CONVERTER

RELATED APPLICATIONS

The present disclosure claims priority to U.S. Provisional Patent Application Ser. No. 62/255,960, filed Nov. 16, 2015, which is incorporated by reference herein in its entirety.

FIELD OF DISCLOSURE

The present disclosure relates in general to circuits for audio devices, including without limitation personal audio devices such as wireless telephones and media players, and more specifically, to a switched mode power supply for supplying a supply voltage to an amplifier or other load.

BACKGROUND

Personal audio devices, including wireless telephones, such as mobile/cellular telephones, cordless telephones, mp3 players, and other consumer audio devices, are in widespread use. Such personal audio devices may include circuitry for driving a pair of headphones or one or more speakers. Such circuitry often includes a power amplifier for driving an audio output signal to headphones or speakers. Generally speaking, a power amplifier amplifies an audio signal by taking energy from a power supply and controlling an audio output signal to match an input signal shape but with a larger amplitude. Although many amplifier architectures (e.g., Class A, Class B, and Class AB amplifiers) provide for only a single power supply for a power amplifier, some architectures provide for at least two supply voltages for powering a power amplifier, in order to achieve greater power efficiency over single or constant power supply voltage architectures.

One example of a multi-supply voltage amplifier is a Class H amplifier. A Class H amplifier may have an infinitely variable voltage supply rail that tracks an envelope of an output signal of the Class H amplifier. In order to provide such an infinitely variable voltage supply rail, the output supply rail may be modulated such that the rail is only slightly larger than a magnitude of the audio output signal at any given time. For example, switched-mode power supplies may be used to create the output signal-tracking voltage rails. Accordingly, a Class H amplifier may increase efficiency by reducing the wasted power at output driving transistors of the amplifier.

SUMMARY

In accordance with the teachings of the present disclosure, one or more disadvantages and problems associated with existing approaches to driving an audio output signal to an audio transducer may be reduced or eliminated.

In accordance with embodiments of the present disclosure, an apparatus may include a power converter having a power supply input for receiving an input power supply voltage generated by a power supply, an output for generating an output voltage to a load, and a power inductor coupled between the power supply input and the output, and further include an energy storage element coupled to the power supply input, the power inductor, and the output such that operation of the power inductor is split temporally between delivering energy to the energy storage element and delivering energy to the load, and operation of the energy storage element is split temporally between delivering energy to the load and receiving energy from one or both of the power supply and the load.

In accordance with these and other embodiments of the present disclosure, a method may include, in a power converter having a power supply input for receiving an input power supply voltage generated by a power supply, an output for generating an output voltage to a load, and a power inductor coupled between the power supply input and the output, and further having an energy storage element coupled to the power supply input, the power inductor, and the output, operating the power converter such that the power inductor is split temporally between delivering energy to the energy storage element and delivering energy to the load, and operating the power converter such that the energy storage element is split temporally between delivering energy to the load and receiving energy from one or both of the power supply and the load.

Technical advantages of the present disclosure may be readily apparent to one skilled in the art from the figures, description and claims included herein. The objects and advantages of the embodiments will be realized and achieved at least by the elements, features, and combinations particularly pointed out in the claims.

It is to be understood that both the foregoing general description and the following detailed description are examples and explanatory and are not restrictive of the claims set forth in this disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present embodiments and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIG. **1** is an illustration of an example personal audio device, in accordance with embodiments of the present disclosure;

FIG. **2** is a block diagram of selected components of an example audio integrated circuit of a personal audio device, in accordance with embodiments of the present disclosure;

FIG. **3** is a block diagram of selected components of an example switched-mode power supply, in accordance with embodiments of the present disclosure;

FIG. **4** illustrates a table setting forth a plurality of useful switch configurations of the switched-mode power supply of FIG. **3**, in accordance with embodiments of the present disclosure;

FIG. **5** illustrates a graph of an example load voltage having a rectified sinusoidal waveform, the graph indicating example ranges for operation in various operational modes of the switched-mode power supply of FIG. **3**, in accordance with embodiments of the present disclosure;

FIG. **6** is a block diagram of selected components of another example switched-mode power supply, in accordance with embodiments of the present disclosure; and

FIG. **7** is a block diagram of selected components of another example audio integrated circuit of a personal audio device, in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION

FIG. **1** is an illustration of an example personal audio device **1**, in accordance with embodiments of the present disclosure. FIG. **1** depicts personal audio device **1** coupled to a headset **3** in the form of a pair of earbud speakers **8**A

and **8**B. Headset **3** depicted in FIG. **1** is merely an example, and it is understood that personal audio device **1** may be used in connection with a variety of audio transducers, including without limitation, headphones, earbuds, in-ear earphones, and external speakers. A plug **4** may provide for connection of headset **3** to an electrical terminal of personal audio device **1**. Personal audio device **1** may provide a display to a user and receive user input using a touch screen **2**, or alternatively, a standard liquid crystal display (LCD) may be combined with various buttons, sliders, and/or dials disposed on the face and/or sides of personal audio device **1**. As also shown in FIG. **1**, personal audio device **1** may include an audio integrated circuit (IC) **9** for generating an analog audio signal for transmission to headset **3** and/or another audio transducer.

FIG. **2** is a block diagram of selected components of an example audio IC **9** of a personal audio device, in accordance with embodiments of the present disclosure. In some embodiments, example audio IC **9** may be used to implement audio IC **9** of FIG. **1**. As shown in FIG. **2**, a microcontroller core **18** may supply a digital audio input signal DIG_IN to a digital-to-analog converter (DAC) **14**, which may convert the digital audio input signal to an analog signal V_{IN}. DAC **14** may supply analog signal V_{IN} to an amplifier stage **16** which may amplify or attenuate audio input signal V_{IN} to provide an audio output signal V_{OUT}, which may operate a speaker, headphone transducer, a line level signal output, and/or other suitable output. A capacitor CO may be utilized to couple the output signal to the transducer or line level output, particularly if amplifier stage **16** is operated from a unipolar power supply having a quiescent voltage substantially differing from ground. Also, as shown in FIG. **2**, audio IC **9** may include a control circuit **20** configured to, based on digital audio input signal DIG_IN, control a power supply voltage of amplifier stage **16** using one or more control signals (labeled as "VOLTAGE CONTROL" in FIG. **2**).

As depicted in FIG. **2**, amplifier stage **16** may include a Class H amplifier **26** which has an input for receiving analog signal V_{IN}, an output for generating output signal V_{OUT} based on and indicative of analog signal V_{IN}, and a power supply input for receiving a variable load voltage V_{LOAD} output by a variable power supply **28**, wherein variable power supply **28** outputs variable load voltage V_{LOAD} based on one or more control signals VOLTAGE CONTROL. Load voltage V_{LOAD} output by variable power supply **28** may be selected from a plurality of discrete voltages, or may include an infinite number of voltages between a minimum and maximum voltage.

FIG. **3** is a block diagram of selected components of an example switched-mode power supply **30**, in accordance with embodiments of the present disclosure. In some embodiments, example switched-mode power supply **30** may be used to implement variable power supply **28** of FIG. **2**. As shown in FIG. **3**, switched-mode power supply **30** may include a battery **40** or other voltage source configured to output a battery voltage V_{BAT}. Battery **40** may comprise any suitable energy storage device, including without limitation one or more electrochemical cells configured to convert chemical energy into electrical energy at the terminals of battery **40**. As shown in FIG. **3**, switched-mode power supply **30** may also include an output at which switched-mode power supply **30** may generate a single-ended load voltage V_{LOAD}.

Switched-mode power supply **30** may comprise a power inductor **42** and a plurality of switches **31-37**. Power inductor **42** may comprise any passive two-terminal electrical component which resists changes in electrical current passing through it and such that when electrical current flowing through it changes, a time-varying magnetic field induces a voltage in power inductor **42**, in accordance with Faraday's law of electromagnetic induction, which opposes the change in current that created the magnetic field.

Each switch **31-37** may comprise any suitable device, system, or apparatus for making a connection in an electric circuit when the switch is enabled (e.g., activated, closed, or on) and breaking the connection when the switch is disabled (e.g., deactivated, open, or off) in response to a control signal received by the switch. For purposes of clarity and exposition, control signals for switches **31-37** (e.g., control signals communicated from control circuit **20**) are not depicted although such control signals would be present to selectively enable and disable switches **31-37**. In some embodiments, a switch **31-37** may comprise an n-type metal-oxide-semiconductor field-effect transistor.

Switch **31** may be coupled between a positive input terminal of the battery **40** and a first terminal of power inductor **42**. Switch **32** may be coupled between a negative input terminal of battery **40** (e.g., a ground voltage) and the first terminal of power inductor **42**. Switch **33** may be coupled between a second terminal of power inductor **42** and the output of switched-mode power supply **30**. Switch **34** may be coupled between the second terminal of power inductor **42** and the negative input terminal of battery **40** (e.g., ground voltage). Switch **35** may be coupled between the second terminal of power inductor **42** and a first terminal of capacitor **44** or another energy storage element. Switch **36** may be coupled between the first terminal of power inductor **42** and the first terminal of capacitor **44**. Switch **37** (which, in some embodiments, may not be present in switched-mode power supply **30**), may be coupled between the output of switched-mode power supply **30** and the first terminal of power inductor **42**.

Capacitor **44** may be coupled at its second terminal to the negative input terminal of battery **40** (e.g., ground voltage). Capacitor **44** may comprise any electrical component used to temporarily store electrical energy in an electric field. In some embodiments, capacitor **44** may be replaced with any other component capable of storing energy. For example, in some embodiments, capacitor **44** may be replaced with a rechargeable battery.

In operation, switches **31-34** may be controlled by control circuit **20** such that switched-mode power supply **30** operates in a plurality of modes including at least a boost mode in which switched-mode power supply **30** generates its output voltage (e.g., load voltage V_{LOAD}) greater than its input power supply voltage (e.g., battery voltage V_{BAT}) and a buck mode in which switched-mode power supply **30** generates its output voltage (e.g., load voltage V_{LOAD}) lesser than its input power supply voltage (e.g., battery voltage V_{BAT}). For example, to operate in a buck mode, control circuit **20** may enable switch **33**, disable switch **34**, and sequentially commutate switches **31** and **32** in a charging phase and discharging phase, respectively. To operate in a boost mode, control circuit **20** may enable switch **31**, disable switch **32**, and sequentially commutate switches **33** and **34** in a charging phase and discharging phase, respectively. Thus, in essence, switched-mode power supply **30** operates as a power converter.

In addition, control circuit **20** may control switches **31-37** such that operation of power inductor **42** is split temporally between delivering energy to capacitor **44** and delivering energy to a load at the output of switched-mode power supply **30** and such that operation of capacitor **44** is split

temporally between delivering energy to the load at the output of switched-mode power supply **30** and receiving energy from one or both of battery **40** and the load at the output of switched-mode power supply **30**. For example, when switch **33** is enabled and switch **35** is disabled, either energy may be delivered to the load at the output of switched-mode power supply **30** from power inductor **42**, or energy may be delivered from the load at the output of switched-mode power supply **30** to power inductor **42**, via the second terminal of power inductor **42**. As a further example, when switch **36** is enabled, energy may be delivered to power inductor **42** from capacitor **44**. Additionally, when switch **37** is enabled, energy may be delivered from the load at the output of switched-mode power supply **30** to power inductor **42**, via the first terminal of power inductor **42**. Further, when switches **35** and **36** are both disabled, capacitor **44** may neither receive energy from nor deliver energy to other components of switched-mode power supply **30**.

As an example of control of switches **31-37**, FIG. **4** illustrates a table setting forth a plurality of useful switch configurations of switched-mode power supply **30**, in accordance with embodiments of the present disclosure. FIG. **4** also sets forth the proposed path of energy transfer for each of the various configurations. With respect to the proposed path of energy transfer for each of the various configurations set forth in FIG. **4**, other voltages present in switched-mode power supply **30** may alter transferring of charge to and from power inductor **42** from those set forth in the right-most column of FIG. **4**, as would be appreciated by those of skill in the relevant art.

In each switching cycle of switched-mode power supply **30**, switched-mode power supply **30** may use two or more of the configurations set forth in FIG. **4** in any suitable sequence to either charge or discharge power inductor **42** and/or to transfer energy to or from a load at the output of switched-mode power supply **30** or transfer energy to or from capacitor **44**. The net effect of using two or more of these switching configurations during a switching cycle maybe either to buck or boost load voltage V_{LOAD} or to buck or boost voltage V_{STR} across capacitor **44**. For example, switched-mode power supply **30** may, during a switching cycle, use a sequence of Config A, Config B, Config G and Config H as shown in FIG. **4**, which may have the net effect of pushing energy to both the load and the storage capacitor. The exact duration of the respective configurations during a switching cycle may control whether load voltage V_{LOAD} or voltage V_{STR} is greater than or less than that of battery voltage V_{BAT}.

FIG. **5** illustrates a graph of an example load voltage V_{LOAD} having a rectified alternating-current waveform with voltage being modified as necessary to control current provided by battery **40** while maintaining desired behavior of load voltage V_{LOAD}, the graph indicating example ranges for operation in various operational modes of switched-mode power supply **30**, in accordance with embodiments of the present disclosure. Thus, for each cycle of an alternating current full-scale signal, switched-mode power supply **30** may sequentially operate in a buck mode (e.g., for $V_{LOAD}<V_{BAT}+\Delta V_1$, wherein ΔV_1 may be an arbitrarily chosen voltage), a boost mode (e.g., for $V_{LOAD}>V_{BAT}\Delta V_2$, wherein ΔV_2 may be an arbitrarily chosen voltage which may or may not be equal to voltage ΔV_1), and then again in the buck mode. FIG. **5** also depicts an example waveform for a voltage V_{STR} across capacitor **44** when load voltage V_{LOAD} has a rectified sinusoidal waveform. As is evident from FIG. **5**, certain intervals of time may exist in which capacitor voltage V_{STR} falls below that of load voltage V_{LOAD}.

Thus, with the switching sequence of FIG. **4** and as demonstrated in FIG. **5**, during the buck mode, energy may be transferred from battery **40** to each of the load and capacitor **44**, and during the boost mode, energy may be transferred from both of battery **40** and capacitor **44** to the load. Accordingly, switched-mode power supply **30** may be able to draw substantially constant power from battery **40** and store unneeded energy pulled from battery **40** in capacitor **44**. When additional energy is needed at the load, energy may be drawn from both battery **40** and capacitor **44**, in some instances without the need to increase power draw from battery **40**. Advantageously, such an architecture and operation may minimize peak currents drawn from battery **40**, which may minimize occurrence of brownouts and other undesirable effects. Also, in the architecture of switched-mode power supply **30**, unlike a standard boost converter, voltage in capacitor **44** may fall below that of battery voltage V_{BAT} and load voltage V_{LOAD}, thus allowing more stored energy of capacitor **44** to be used than that of a boost capacitor in a boost converter.

Although capacitor **44** is shown as integral to switched-mode power supply **30**, in some embodiments, a single capacitor **44** may be electrically coupled to multiple switched-mode power supplies or other components, and thus its functionality as described above may be shared among multiple switched-mode power supplies.

Although the foregoing contemplates certain switching configurations associated with certain modes (e.g., boost mode or buck mode), it is noted that operation in a certain mode does not necessarily imply any certain switch configuration. For example, when load voltage V_{LOAD} is approximately equal to battery voltage V_{BAT}, operation in a conventional buck or boost configuration may not be possible due to the fact such operation may require excessively small switching times of switches of switched-mode power supply **30**. Accordingly, in such scenarios, a buck-boost or triphase switching configuration may be used, with the new effect of a boosting or bucking of voltage.

FIG. **6** is a block diagram of selected components of another example switched-mode power supply **50**, in accordance with embodiments of the present disclosure. In some embodiments, example switched-mode power supply **50** may be used to implement variable power supply **28** of FIG. **2**.

As shown in FIG. **6**, switched-mode power supply **50** may include a battery **61** or other voltage source configured to output a battery voltage V_{BAT}. Battery **61** may comprise any suitable energy storage device, including without limitation one or more electrochemical cells configured to convert chemical energy into electrical energy at the terminals of battery **61**. As shown in FIG. **6**, switched-mode power supply **50** may also include an output at which switched-mode power supply **50** may generate a differential load voltage V_{LOAD}.

Switched-mode power supply **50** may comprise a power inductor **62** and a plurality of switches **51-60**. Power inductor **62** may comprise any passive two-terminal electrical component which resists changes in electrical current passing through it and such that when electrical current flowing through it changes, a time-varying magnetic field induces a voltage in power inductor **62**, in accordance with Faraday's law of electromagnetic induction, which opposes the change in current that created the magnetic field.

Each switch **51-60** may comprise any suitable device, system, or apparatus for making a connection in an electric

circuit when the switch is enabled (e.g., activated, closed, or on) and breaking the connection when the switch is disabled (e.g., deactivated, open, or off) in response to a control signal received by the switch. For purposes of clarity and exposition, control signals for switches **51-60** (e.g., control signals communicated from control circuit **20**) are not depicted, although such control signals would be present to selectively enable and disable switches **51-60**. In some embodiments, a switch **51-60** may comprise an n-type metal-oxide-semiconductor field-effect transistor.

Switch **51** may be coupled between a positive input terminal of the battery **61** and a first terminal of power inductor **62**. Switch **52** may be coupled between a negative input terminal of battery **61** (e.g., a ground voltage) and the first terminal of power inductor **62**. Switch **53** may be coupled between the positive input terminal of the battery **61** and a second terminal of power inductor **62**. Switch **54** may be coupled between the negative input terminal of battery **61** (e.g., a ground voltage) and the second terminal of power inductor **62**. Switch **55** may be coupled between the second terminal of power inductor **62** and a positive output terminal of switched-mode power supply **50**. Switch **56** may be coupled between the first terminal of power inductor **62** and a negative output terminal of switched-mode power supply **50**. Switch **57** may be coupled between the positive output terminal of switched-mode power supply **50** and the negative input terminal of battery **61** (e.g., a ground voltage). Switch **57** may be coupled between the negative output terminal of switched-mode power supply **50** and the negative input terminal of battery **61** (e.g., a ground voltage). Switch **59** may be coupled between the first terminal of power inductor **62** and a first terminal of a capacitor **64**. Switch **60** may be coupled between the second terminal of power inductor **62** and the first terminal of a capacitor **64**.

Capacitor **64** may be coupled at its second terminal to the negative input terminal of battery **61** (e.g., ground voltage). Capacitor **64** may comprise any electrical component used to temporarily store electrical energy in an electric field. In some embodiments, capacitor **64** may be replaced with any other component capable of storing energy. For example, in some embodiments, capacitor **64** may be replaced with a rechargeable battery.

In operation, switches **51-58** may be controlled by control circuit **20** such that switched-mode power supply **50** operates in a plurality of modes including at least a boost mode in which switched-mode power supply **50** generates its output voltage (e.g., load voltage V_{LOAD}) greater than its input power supply voltage (e.g., battery voltage V_{BAT}) and a buck mode in which switched-mode power supply **50** generates its output voltage (e.g., load voltage V_{LOAD}) lesser than its input power supply voltage (e.g., battery voltage V_{BAT}). In addition, such switches **51-58** may be controlled by control circuit **20** such that switched-mode power supply **50** may output either positive or negative voltages of load voltage V_{LOAD}, in contrast to switched-mode power supply **30** of FIG. **3**, which may be capable of only generating positive voltages of load voltage V_{LOAD}.

To illustrate, when generating a positive load voltage V_{LOAD}, to operate in a buck mode, control circuit **20** may enable switches **55** and **58**, disable switches **53**, **54**, **56** and **57**, and sequentially commutate switches **51** and **52**. To operate in a boost mode when generating a positive load voltage V_{LOAD}, control circuit **20** may enable switches **51** and **58**, disable switches **52**, **53**, **56**, and **57**, and sequentially commutate switches **54** and **55**. On the other hand, when generating a negative load voltage V_{LOAD}, to operate in a buck mode, control circuit **20** may enable switches **56** and **57**, disable switches **51**, **52**, **55** and **58**, and sequentially commutate switches **53** and **54**. To operate in a boost mode when generating a negative load voltage V_{LOAD}, control circuit **20** may enable switches **53** and **57**, disable switches **51**, **54**, **55**, and **58**, and sequentially commutate switches **52** and **56**. Thus, in essence, switched-mode power supply **30** operates as a power converter with a differential output that can generate either positive or negative values for load voltage V_{LOAD}.

In addition, control circuit **20** may control switches **51-60** such that operation of power inductor **62** is split temporally between delivering energy to capacitor **64** and delivering energy to a load at the output of switched-mode power supply **50** and such that operation of capacitor **64** is split temporally between delivering energy to the load at the output of switched-mode power supply **50** and receiving energy from one or both of battery **61** and the load at the output of switched-mode power supply **50**. For example, when either of switches **55** and **56** is enabled and switches **59** and **60** are disabled, either energy may be delivered to the load at the output of switched-mode power supply **50** from power inductor **62**, or energy may be delivered from the load at the output of switched-mode power supply **50** to power inductor **62**. As another example, when switches **55** and **60** are enabled, either energy may be delivered to the load at the output of switched-mode power supply **50** from capacitor **64**, or energy may be delivered from the load at the output of switched-mode power supply **50** to capacitor **64**. As a further example, when either of switches **59** and **60** is enabled, energy may be delivered to power inductor **62** from capacitor **64**. Further, when switches **59** and **60** are both disabled, capacitor **44** may neither receive energy from nor deliver energy to other components of switched-mode power supply **30**.

Switched-mode power supply **50** may be seen as the differential-output equivalent to the single-ended implementation of switched-mode power supply **30**.

Although the foregoing discussion has contemplated that switched-mode power supply **30** and switched-mode power supply **50** may be used as a variable voltage supply to an audio amplifier for processing an audio signal, in some embodiments, switched-mode power supply **30** and/or switched-mode power supply **50** may be used to generate an audio output signal within an amplifier, rather than supplying a supply voltage to such an amplifier for operation of the amplifier. For example, FIG. **7** is a block diagram of selected components of an example switched-mode amplifier **70**, in accordance with embodiments of the present disclosure. In some embodiments, switched-mode amplifier **70** may be used in lieu of amplifier **16** described with respect to FIG. **2**. As shown in FIG. **7**, switched-mode amplifier **70** may comprise a loop filter **72**, a switched-mode converter controller **74**, and a switched-mode power supply **76**.

Loop filter **72** may comprise any system, device, or apparatus configured to receive an input signal (e.g., digital audio input signal DIG_IN or a derivative thereof) and a feedback signal (e.g., audio output signal $\backslash T_{our}$, a derivative thereof, or other signal indicative of audio output signal V_{OUT}) and based on such input signal and feedback signal, generate a controller input signal to be communicated to switched-mode power supply controller **74**. In some embodiments, such controller input signal may comprise a signal indicative of an integrated error between the input signal and the feedback signal. In other embodiments, such controller input signal may comprise a signal indicative of a target current signal to be driven as an output current I_{OUT}

or a target voltage signal to be driven as an output voltage V_{OUT} to a load coupled to the output terminals of switched-mode power supply **76**.

Switched-mode power supply controller **74** may comprise any system, device, or apparatus configured to, based on the controller input signal, sequentially select among a plurality of switch configurations of switched-mode power supply **76** and based on an input signal (e.g., digital audio input signal DIG_IN), output signal V_{OUT}, and/or other characteristics of switched-mode amplifier **70**, communicate a plurality of control signals to switched-mode power supply **76** to apply a switch configuration from a plurality of switch configurations of switches (e.g., switches **31-37** or switches **51-60**) of switched-mode power supply **76** to selectively activate or deactivate each of the plurality of switches in order to transfer electrical energy from a battery or other power supply providing a voltage V_{BAT} to the load of switched-mode amplifier **70** in accordance with the input signal.

Switched-mode power supply **76** may receive a voltage V_{BAT} at its input, and may generate at its output audio output signal V_{OUT}. Although not explicitly shown in FIG. **7**, in some embodiments, voltage V_{BAT} may be received via input terminals including a positive input terminal and a negative input terminal which may be coupled to a ground voltage. Switched-mode power supply **76** may comprise a power inductor (e.g., power inductor **42** or power inductor **62**) and a plurality of switches (e.g., switches **31-37** or switches **51-60**) that are controlled by control signals received from switched-mode power supply controller **74** in order to convert voltage V_{BAT} to audio output signal V_{OUT}, such that audio output signal V_{OUT} is a function of the input signal to loop filter **72**. Switched-mode power supply **76** may be implemented by switched-mode power supply **30**, switched-mode power supply **50**, or any other suitable circuit.

As used herein, when two or more elements are referred to as "coupled" to one another, such term indicates that such two or more elements are in electronic communication or mechanical communication, as applicable, whether connected indirectly or directly, with or without intervening elements.

This disclosure encompasses all changes, substitutions, variations, alterations, and modifications to the exemplary embodiments herein that a person having ordinary skill in the art would comprehend. Similarly, where appropriate, the appended claims encompass all changes, substitutions, variations, alterations, and modifications to the exemplary embodiments herein that a person having ordinary skill in the art would comprehend. Moreover, reference in the appended claims to an apparatus or system or a component of an apparatus or system being adapted to, arranged to, capable of, configured to, enabled to, operable to, or operative to perform a particular function encompasses that apparatus, system, or component, whether or not it or that particular function is activated, turned on, or unlocked, as long as that apparatus, system, or component is so adapted, arranged, capable, configured, enabled, operable, or operative.

All examples and conditional language recited herein are intended for pedagogical objects to aid the reader in understanding the invention and the concepts contributed by the inventor to furthering the art, and are construed as being without limitation to such specifically recited examples and conditions. Although embodiments of the present inventions have been described in detail, it should be understood that various changes, substitutions, and alterations could be made hereto without departing from the spirit and scope of the disclosure.

What is claimed is:

1. An apparatus comprising:

a power converter having a power supply input for receiving an input power supply voltage generated by a power supply, an output for generating an output voltage to a load, and a power inductor coupled between the power supply input and the output; and

an energy storage element coupled to the power supply input, the power inductor, and the output such that:

within a first portion of a single switching cycle, the power inductor is configured both to deliver energy to the energy storage element; and

within a second, different portion of the same single switching cycle, the power inductor is configured to deliver energy to the load.

2. The apparatus of claim **1**, wherein the power converter comprises a switched-mode power supply comprising a plurality of switches configured to be controlled such that the power converter operates in a plurality of modes comprising at least:

a boost mode in which the power converter generates the output voltage greater than the input power supply voltage; and

a buck mode in which the power converter generates the output voltage lesser than the input power supply voltage.

3. The apparatus of claim **2**, wherein at least one switching cycle of the power converter in the boost mode comprises a charging phase and a discharging phase such that:

during the charging phase, the power inductor is charged from the power supply and the energy storage element; and

during the discharging phase, the power inductor is discharged to the load.

4. The apparatus of claim **2**, wherein at least one switching cycle of the power converter in the buck mode comprises a charging phase and a discharging phase such that:

during the charging phase, the power inductor is charged from the power supply; and

during the discharging phase, the power inductor is discharged to the load and the energy storage element.

5. The apparatus of claim **1**, wherein the energy storage element comprises a capacitor.

6. The apparatus of claim **5**, wherein:

the power supply comprises a first power supply terminal and a second power supply terminal;

the first power supply terminal is coupled to the power supply input of the power converter; and

the capacitor has a first capacitor terminal coupled to the power inductor and a second capacitor terminal coupled to the second power supply terminal.

7. The apparatus of claim **1**, wherein the power inductor comprises a first inductor terminal coupled to the power supply input and a second inductor terminal coupled to a first storage element terminal of the energy storage element, and the apparatus further comprises a first switch coupled between the second inductor terminal and the load, such that when the first switch is enabled, either energy is delivered to the load from at least one of the energy storage element and the power inductor, or energy is delivered from the load to at least one of the energy storage element and the power inductor.

8. The apparatus of claim **7**, further comprising a second switch coupled between the first storage element terminal of the energy storage element and the first inductor terminal,

such that when the second switch is enabled, energy is delivered to the power inductor from the energy storage element.

9. The apparatus of claim **7**, further comprising a second switch coupled between the first storage element terminal of the energy storage element and the load, such that when the second switch is enabled, energy is delivered to the energy storage element from the load.

10. The apparatus of claim **1**, wherein operation of the energy storage element is split temporally among delivering energy to the load, receiving energy from one or both of the power supply and the load, and neither delivering nor receiving energy.

11. A method comprising, in a power converter having a power supply input for receiving an input power supply voltage generated by a power supply, an output for generating an output voltage to a load, and a power inductor coupled between the power supply input and the output and further having an energy storage element coupled to the power supply input, the power inductor, and the output:

operating the power converter such that;

within a first portion of a single switching cycle, the power inductor delivers energy to the energy storage element; and

within a second, different portion of the same single switching cycle, the power inductor delivers energy to the load.

12. The method of claim **11**, wherein the power converter comprises a switched-mode power supply comprising a plurality of switches, the method comprising controlling the plurality of switches such that the power converter operates in a plurality of modes comprising at least:

a boost mode in which the power converter generates the output voltage greater than the input power supply voltage; and

a buck mode in which the power converter generates the output voltage lesser than the input power supply voltage.

13. The method of claim **12**, wherein at least one switching cycle of the power converter in the boost mode comprises a charging phase and a discharging phase, the method further comprising:

during the charging phase, operating the power converter such that the power inductor is charged from the power supply and the energy storage element; and

during the discharging phase, operating the power converter such that the power inductor is discharged to the load.

14. The method of claim **12**, wherein at least one switching cycle of the power converter in the buck mode comprises a charging phase and a discharging phase, the method further comprising:

during the charging phase, operating the power converter such that the power inductor is charged from the power supply; and

during the discharging phase, operating the power converter such that the power inductor is discharged to the load and the energy storage element.

15. The method of claim **11**, wherein the energy storage element comprises a capacitor.

16. The method of claim **15**, wherein:

the power supply comprises a first power supply terminal and a second power supply terminal;

the first power supply terminal is coupled to the power supply input of the power converter; and

the capacitor has a first capacitor terminal coupled to the power inductor and a second capacitor terminal coupled to the second power supply terminal.

17. The method of claim **11**, wherein the power inductor comprises a first inductor terminal coupled to the power supply input and a second inductor terminal coupled to a first storage element terminal of the energy storage element, the method further comprising controlling a first switch coupled between the second inductor terminal and the load, such that when the first switch is enabled, either energy is delivered to the load from at least one of the energy storage element and the power inductor, or energy is delivered from the load to at least one of the energy storage element and the power inductor.

18. The method of claim **17**, further comprising controlling a second switch coupled between the first storage element terminal of the energy storage element and the first inductor terminal, such that when the second switch is enabled, energy is delivered to the power inductor from the energy storage element.

19. The method of claim **17**, further comprising controlling a second switch coupled between the first storage element terminal of the energy storage element and the load, such that when the second switch is enabled, energy is delivered to the energy storage element from the load.

20. The method of claim **11**, further comprising operating the power converter such that operation of the energy storage element is split temporally among delivering energy to the load, receiving energy from one or both of the power supply and the load, and neither delivering nor receiving energy.

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