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(71) Applicant *(for all designated States except US)*: **TEXAS INSTRUMENTS INCORPORATED** [US/US]; P.o. Box 655474, Mail Station 3999, Dallas, TX 75265-5474 (US).

(71) Applicant *(for JP only)*: **TEXAS INSTRUMENTS JAPAN LIMITED** [JP/JP]; 24-1, Nishi-shinjuku 6 Chome, Shinjuku-ku, Tokyo, 160-8366 (JP).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **IVANOV, Vadim, V.** [US/US]; 5195 S. Freemen Road, Tucson, AZ (US). **SCOONES, Kevin, A.** [US/US]; 5555 E. Mockingbird Lane, Dallas, TX 75206 (US).

(74) Agents: **FRANZ, Warren, L.** et al.; Texas Instruments Incorporated, Deputy General Patent Counsel, P.O. Box 655474, Mail Station 3999, Dallas, TX 75265-5474 (US).

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(54) **Title**: BATTERY PROTECTION CIRCUIT AND METHOD FOR ENERGY HARVESTER CIRCUIT

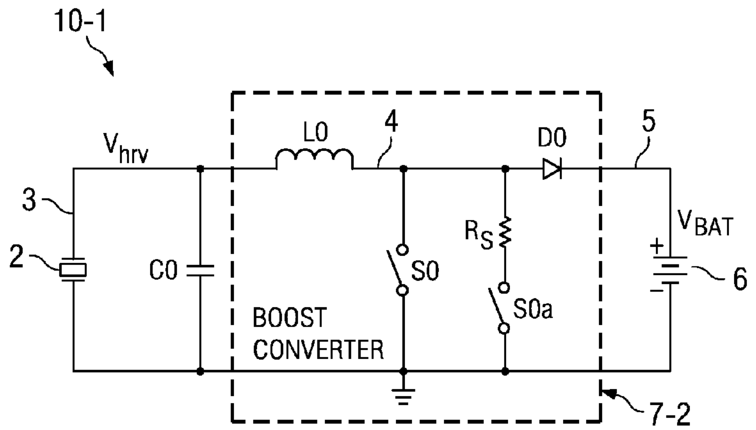

FIG. 2

(57) **Abstract**: Power management circuitry (7-2,3,4) for converting a harvested voltage (V_{hrv}) to an output voltage (V_{BAT}) applied to a battery (6) includes an inductor (LO) having a first terminal (3) coupled to receive the harvested voltage (V_{hrv}) and a second terminal coupled to a first terminal of a first switch (SO). The power management circuitry transfers the current generated by an energy harvester (2) to the battery if it (6) is not fully charged, and shunts the current away from the battery (6) to avoid over-charging if it is fully charged.

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BATTERY PROTECTION CIRCUIT AND METHOD FOR ENERGY HARVESTER CIRCUIT

[0001] The invention relates generally to energy harvesters, such as vibration energy harvesters, for scavenging or harvesting very low levels of energy, and more particularly to circuits and methods for protecting batteries or super capacitors in which the harvested energy is stored.

[0002] The invention also relates to circuits and methods for preventing surge current damage to inductors and/or other circuit components in DC-DC converter circuits or other power management circuitry that receives energy from the outputs of energy harvesters.

BACKGROUND

[0003] Various very low power, i.e., “nanopower”, integrated circuits that require extremely low amounts of operating current have been developed which can be powered by very small amounts of power scavenged or harvested from ambient solar, vibrational, thermal, and/or biological energy sources by means of micro-energy harvesting devices and then stored in batteries or super capacitors. (The term “nanopower” as used herein is intended to encompass circuits and/or circuit components which draw DC current of less than roughly 1 microampere.) The amount of energy available from a harvester usually is small and unpredictable, so intermediate energy storage is often required in these applications to provide for system power needs when energy from the harvester is unavailable or insufficient. Lithium batteries or super capacitors are commonly used for such intermediate energy storage.

[0004] FIG. 1 shows a circuit 1 including an energy harvester 2 which produces a DC voltage V_{hrv} on a conductor 3 that is connected to one terminal of a large filter capacitor C0 and to the input of a conventional boost converter 7-1. Boost converter 7-1 includes an inductor L0 coupled between V_{hrv} and conductor 4, which is connected to one terminal of a switch S0 and to the anode of a diode D0. The other terminal of switch S0 is connected to ground. The cathode of diode D0 is connected by conductor 5 to the (+) terminal of a battery or super capacitor 6.

[0005] Suitable power management circuitry for energy harvester 2 controls switch S0 so as to provide charging of battery/super capacitor 6 when energy is available from harvester 2 if battery/super capacitor 6 is not fully charged to its maximum or fully-charged voltage $V_{BAT(max)}$. (For a typical lithium battery, $V_{BAT(max)}$ is 4.5 volts.)

[0006] If battery 6 is fully charged to $V_{BAT(max)}$, then further charging may permanently damage it. In the unprotected system of FIG. 1 there is nothing to prevent current from harvester 2 from overcharging battery/super capacitor 6. However, the output voltage V_{hrv} generated by harvester 2 should be limited to a value below $V_{BAT(max)}$ to prevent damage to the battery/super capacitor. Furthermore, such limiting of V_{hrv} should prevent surge currents supplied by charged-up filter capacitor C0 from damaging circuit components such as inductor L0 and/or other circuit components in the power management circuitry.

SUMMARY

[0007] Embodiments of the invention provide power management circuitry (7-2,3,4) for converting a harvested voltage (V_{hrv}) to an output voltage (V_{BAT}) applied to an energy storage device (6) that includes an inductor (L0) having a first terminal (3) coupled to receive the harvested voltage (V_{hrv}) and a second terminal coupled to a first terminal of a first switch (S0). The power management circuitry transfers the current generated by an energy harvester (2) to the energy storage device if it is not fully charged, and shunts the current away from the energy storage device (6) to avoid overcharging it if it is fully charged.

[0008] In one embodiment, the invention provides an energy harvesting system (10-1,2,3) including an energy harvester (2) for generating a harvested voltage (V_{hrv}) and an energy management circuit (7-2,3,4) for converting the harvested voltage (V_{hrv}) to an output voltage (V_{BAT}). The energy management circuit (7-2,3,4) includes an inductor (L0) having a first terminal (3) coupled to receive the harvested voltage (V_{hrv}) and a second terminal (4) coupled to a first terminal of a first switch (S0). An energy storage device (6) is coupled to receive the output voltage (V_{BAT}). Protection circuitry (S0a,R_S in FIG. 2; S1,R_S,15-1,2 in FIG. 3,4) in the energy management circuit (7-2,3,4) shunts current generated by the energy harvester (2) away from the energy storage device (6) if the energy storage device (6) is fully charged. The energy management circuit (7-2,3,4) includes a control circuit (15-1,2) coupled to a control terminal of the first switch (S0).

[0009] In one embodiment, the energy management circuit (7-3,4) includes a second switch (S1) coupled in parallel with the energy harvester (2) to perform the shunting, and the second switch (S1) has a control terminal coupled to the control circuit (15-1,2) to control the shunting. In one embodiment, a first terminal of the second switch (S1) is coupled to a first reference voltage (GND), a second terminal of the second switch (S1) is coupled to a first terminal of a current-limiting resistor (R_S), and a second terminal of the current-limiting resistor

(R_S) is coupled to the first terminal (3) of the inductor (L0). In one embodiment, the energy harvesting system includes a filter capacitor (C0) coupled in parallel with the energy harvester (2). In one embodiment, the energy management circuit (7-2,3,4) includes a rectifying element (D0) coupled between the second terminal (4) of the inductor (L0) and the output voltage (V_{BAT}). In a described embodiment, the energy management circuit (7-2,3,4) includes a boost converter.

[0010] In one embodiment, the control circuit (15-1,2) is coupled to receive the harvested voltage (V_{hrv}) and the output voltage (V_{BAT}) and operates to compare the output voltage (V_{BAT}) to a maximum energy storage device reference voltage ($V_{BAT(max)}$) to determine whether the energy storage device (6) is fully charged, and also operates to maintain the first switch (S0) open and the second switch (S1) closed to shunt the current generated by the energy harvester (2) away from the inductor (L0) and the energy storage device (6) if the energy storage device (6) is fully charged. In one embodiment, the control circuit (15-1,2) operates to compare the harvested voltage (V_{hrv}) to the output voltage (V_{BAT}), maintain the second switch (S1) open, and operate the first switch (S0) so as to effectuate boosting of the harvested voltage (V_{hrv}) by the energy management circuit (7-2,3,4) if the harvested voltage (V_{hrv}) is less than the output voltage (V_{BAT}).

[0011] In a described embodiment, the control circuit (15-1,2) operates to maintain the first (S0) and second (S1) switches open if the harvested voltage (V_{hrv}) is less than the output voltage (V_{BAT}) and the energy storage device (6) is less than fully charged.

[0012] In a described embodiment, the control circuit (15-2) includes a comparator (12) having a first input (-) coupled to receive the harvested voltage (V_{hrv}), a second input (+) coupled to receive a voltage (50) indicating that the energy storage device (6) is fully charged, and an output coupled to the control terminal of the second switch (S1), and wherein the control circuit (15-2) includes an amplifier (17) having a first input (-) coupled to receive the output voltage (V_{BAT}), a second input (+) coupled to receive the maximum energy storage device reference voltage ($V_{BAT(max)}$), and an output coupled by means of a pulse width modulation (PWM) circuit (42) to the control terminal of the first switch (S0).

[0013] In a described embodiment, the energy management circuit (7-2) includes a second switch (S0a) coupled in parallel with the first switch (S0) to perform the shunting. The second switch (S0a) has a control terminal coupled to the control circuit (15-1) to control the shunting. A first terminal of the second switch (S0a) is coupled to a first reference voltage

(GND), and a second terminal of the second switch (S0a) is coupled to the second terminal (4) of the inductor (L0).

[0014] In one embodiment, a current-limiting resistor (R_S) couples the second terminal of the second switch (S0a) to the second terminal (4) of the inductor (L0), and the control circuit (15-1) is coupled to receive the harvested voltage (V_{hrv}) and the output voltage (V_{BAT}) and operates to compare the output voltage (V_{BAT}) to a maximum energy storage device reference voltage ($V_{BAT(max)}$) to determine whether the energy storage device (6) is fully charged. The control circuit (15-1) also operates to maintain the first switch (S0) open and the second switch (S0a) closed to shunt the current generated by the energy harvester (2) away from the energy storage device (6) if the energy storage device (6) is fully charged.

[0015] In one embodiment, the control circuit (15-1) operates to compare the harvested voltage (V_{hrv}) to the output voltage (V_{BAT}), and maintains the second switch (S0a) open and operates the first switch (S0) so as to effectuate boosting of the harvested voltage (V_{hrv}) by the energy management circuit (7-2) if the harvested voltage (V_{hrv}) is less than the output voltage (V_{BAT}).

[0016] In one embodiment, the invention provides a method for harvesting energy from an energy harvester (2) to generate a harvested voltage (V_{hrv}), the method including converting the harvested voltage (V_{hrv}) to an output voltage (V_{BAT}) applied to an energy storage device (6) by means of an energy management circuit (7-2,3,4) including an inductor (L0) having a first terminal (3) coupled to receive the harvested voltage (V_{hrv}) and a second terminal (4) coupled to a first terminal of a first switch (S0); transferring current generated by the energy harvester (2) to the energy storage device (6) by means of the energy management circuit (7-2,3,4) if the energy storage device (6) is not fully charged; and shunting the current generated by the energy harvester (2) away from the energy storage device (6) to avoid overcharging the energy storage device (6) if it is fully charged.

[0017] In one embodiment, the method includes shunting the current generated by the energy harvester (2) away from the inductor (L0). In one embodiment, the method includes coupling the first terminal (3) of the inductor (L0) through a current-limiting resistor (R_S) and a second switch (S1) coupled in parallel with the energy harvester (2) to a reference voltage (GND). In one embodiment, the method includes coupling the second terminal (4) of the inductor (L0) through a current-limiting resistor (R_S) and a second switch (S0a) to a reference voltage (GND). In one embodiment, the method includes operating a control circuit (15-1,2) to maintain the first switch (S0) open and the second switch (S1) closed if the harvested voltage (V_{hrv}) is greater than the output voltage (V_{BAT}).

[0018] In one embodiment, the invention provides a system for harvesting from an energy harvester (2) to generate a DC harvested voltage (V_{hrv}), including means (7-1,2) for converting the harvested voltage (V_{hrv}) to an output voltage (V_{BAT}) applied to an energy storage device (6) by means of an energy management circuit (7-2,3,4) including an inductor (L0) having a first terminal (3) coupled to receive the harvested voltage (V_{hrv}) and a second terminal (4) coupled to a first terminal of a first switch (S0); means (L0,15-1,D0) for transferring current generated by the energy harvester (2) to the energy storage device (6) by means of the energy management circuit (7-2,3,4) if the energy storage device (6) is not fully charged; and means (15-1,2; S1; R_S; S0a) for shunting the current generated by the energy harvester (2) away from the energy storage device (6) to avoid overcharging the energy storage device (6) if it is fully charged.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Example embodiments are described with reference to accompanying drawings, wherein:

[0020] FIG. 1 is a schematic diagram of a conventional boost converter coupled to an energy harvester, for charging a battery or super capacitor.

[0021] FIG. 2 is a schematic diagram including a first circuit for preventing overcharging of the battery in FIG. 1 while also preventing damage to the inductor.

[0022] FIG. 3 is a schematic diagram including a second circuit for preventing overcharging of the battery in FIG. 1 while also preventing damage to the inductor.

[0023] FIG. 4 is a more detailed diagram of the circuitry shown in FIG. 3.

[0024] FIG. 5 is a flowchart of the operation of the boost control circuit in of FIGS. 3 and 4.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0025] FIG. 2 shows a circuit 10-1 including energy harvester 2 which produces a harvested voltage V_{hrv} on a conductor 3. (V_{hrv} either is a DC voltage generated by a suitable rectifier that rectifies AC energy generated by a harvester such as an inductive or piezo electric harvester, or is a DC voltage directly generated by a harvester such as a thermopile harvester or a solar cell harvester.) Conductor 3 is connected to one terminal of filter capacitor C0 and also to the input of a conventional boost converter 7-2. The other terminal of capacitor C0 is connected to ground. Boost converter 7-2 can be considered to be a power management circuit that controls the flow of harvested energy from conductor 4 to battery/super capacitor 6 and/or a load.

[0026] Boost converter 7-2 includes inductor L0 coupled between conductor 3 and conductor 4. As in FIG. 1, conductor 4 in FIG. 2 is connected to one terminal of switch S0 and to the anode of diode D0. The other terminal of switch S0 is connected to ground. The cathode of diode D0 is connected by output conductor 5 to the (+) terminal of battery or super capacitor 6, hereinafter referred to simply as battery 6.

[0027] In accordance with one embodiment of the invention, an additional switch S0a is coupled between ground and one terminal of a current-limiting resistor R_S. A second terminal of current-limiting resistor R_S is connected to conductor 4. Current limiting resistor R_S may have a resistance of a few megohms. Switches S0 and S0a are controlled by a suitable boost control circuit, subsequently described, which compares V_{BAT} with $V_{BAT(max)}$ to determine whether battery 6 is fully charged. The boost controller circuit also determines if V_{hrv} is greater than V_{BAT}.

[0028] It should be appreciated that filter capacitor C0 typically may have a capacitance of roughly 1 μF. Therefore, even though the power available from harvester 2 is very low, if filter capacitor C0 is charged up and switch S0 then is closed, a very large surge of current will be supplied by capacitor C0 through inductor L0. The large surge current would be likely to destroy or seriously damage inductor L0.

[0029] Note that switch S0 in FIG. 1 is a large, low-resistance switch, and it would be possible to provide a gate driver circuit for an MOS transistor implementation of switch S0. In this case, the gate driver circuit could limit the gate drive voltage of the transistor switch so as to provide a higher ON resistance of switch S0, as an alternative to providing current-limiting resistor R_S and switch S0a as in FIG. 2. In this case, switch S0 could be closed when battery 6 is fully charged and its higher ON resistance would prevent overcharging of battery 6 and also prevent damage to inductor L0 by a current surge from filter capacitor C0.

[0030] FIG. 3 shows another embodiment of the invention. As in FIG. 2, circuit 10-2 in FIG. 3 includes energy harvester 2 which produces harvested voltage V_{hrv} on conductor 3. Conductor 3 is connected to one terminal of filter capacitor C0 and also to the input of a conventional boost converter 7-3. The other terminal of capacitor C0 is connected to ground. Boost converter 7-3 can be considered to be a power management circuit that controls the flow of harvested energy from conductor 4 to battery 6 and/or a load. Boost converter 7-3 includes inductor L0 coupled between conductor 3 and conductor 4. Conductor 4 is connected to one terminal of switch S0 and to the anode of diode D0. The other terminal of switch S0 is connected to ground. The cathode of diode D0 is connected by output conductor 5 to the (+) terminal of battery 6.

[0031] In accordance with another embodiment of the invention, switch S1 in FIG. 3 is coupled between ground and one terminal of current-limiting resistor R_S. A second terminal of current-limiting resistor R_S is connected to conductor 3. A booster control circuit 15-1 has an output 20 connected to the control terminal of switch S1 and another output 22 connected to the control terminal of switch S0. Booster control circuit 15-1 has inputs connected to receive the harvester output voltage V_{hrv} on conductor 3, the battery voltage V_{BAT} on conductor 5, and a reference voltage $V_{BAT(max)}$ that represents the fully-charged value of V_{BAT}.

[0032] Switches S0 and S1 are controlled by boost control circuit 15-1, which compares V_{BAT} with V_{BAT}(max) to determine whether battery 6 is fully charged. If battery 6 is fully charged, then boost control circuit 15-1 also determines if V_{hrv} is greater than V_{BAT}. Booster control circuit 15-1 operates in accordance with the flow chart of FIG. 5.

[0033] Referring to decision block 31 in FIG. 5, boost control circuit 15-1 determines if both: (1) V_{hrv} is greater than V_{BAT}, and (2) V_{BAT} is greater than or equal to $V_{BAT(max)}$. If this determination is affirmative, then boost control circuit 15-1 maintains switch S0 open, and also maintains switch S1 closed to prevent harvested current from overcharging the fully-charged battery 6 and to prevent surge currents supplied by filter capacitor C0 from damaging inductor L0 or battery 6. Maintaining switch S1 closed has the effect of directing all of the energy stored in filter capacitor C0 and all of the energy being generated by harvester 2 through current-limiting resistor R_S and switch S1 as long as battery 6 remains fully charged. (It should be appreciated that in the described energy harvesting applications, the amount of energy stored in filter capacitor C0 and the amount of energy being generated by harvester 2 are relatively low, so there is little danger of switch S1 being damaged by current therein. However, if the input of boost converter 7-3 is connected to a sufficiently large energy source, switch S1 would be destroyed.) The algorithm of FIG. 5 goes from block 32 to the entry point of decision block 31 and continues to monitor the value of V_{BAT}.

[0034] If the determination of decision block 31 is negative, then boost control circuit 15-1 determines whether V_{BAT} exceeds $V_{BAT(max)}$, as indicated in decision block 33. If the determination of decision block 33 is affirmative, boost control circuit 15-1 goes to block 34 and keeps switch S0 open and switch S1 closed and returns to the entry point of decision block 31.

[0035] If the determination of decision block 33 is negative, boost control circuit 15-1 goes to decision block 35 and determines if V_{BAT} is nearly equal to $V_{BAT(max)}$. If this decision is affirmative, then boost control circuit 15-1 operates switch S0 at a reduced duty cycle and keeps switch S1 open, to reduce the amount of current through inductor L0; the algorithm then returns to the entry point of decision block 31. If the determination of decision block 35 is negative, then boost control circuit 15-1 operates switch S0 at a normal duty cycle, and keeps switch S1 open, as indicated in block 37, to allow filter capacitor C0 be charged up to V_{hrv} and also to allow normal charging of battery 6.

[0036] Then boost control circuit 15-1 goes to decision block 38 and determines whether V_{hrv} is less than but nearly equal to V_{BAT}. If this determination is affirmative, boost control circuit 15-1 maintains switch S0 open and maintains switch S1 closed, as indicated in block 39, to prevent further charging of battery 6; boost control circuit 15-1 then returns to the entry point of decision block 31. If the determination of decision block 38 is negative, the algorithm allows normal duty cycle operation of switch S0 to continue and returns to the entry point of decision block 31.

[0037] It should be understood that the flowchart of FIG. 5 is also applicable to the operation of a boost control circuit utilized to control switches S0 and S0a in FIG. 2 if switch “S1” in blocks 32, 34, and 35 is replaced by a switch “S0a”.

[0038] FIG. 4 shows a circuit 10-3 which is the same as circuit 10-2 in FIG. 3, but with further detail in booster control circuit 15-2. Booster control circuit 15-2 includes a comparator 12 having its (-) input connected to receive V_{hrv} on conductor 3 and its (+) input coupled to receive, via conductor 50, the output of a comparator 43 having its (+) input coupled to V_{BAT} and its (-) input coupled to receive $V_{BAT(max)}$. The output of comparator 12 is connected by conductor 20 to the control terminal of switch S1. An amplifier 17 has its (-) input coupled to receive the present battery voltage V_{BAT} on conductor 5 and its (+) input coupled to receive the reference voltage $V_{BAT(max)}$ on conductor 16. The output of amplifier 17 can be connected to the input of a conventional pulse width modulation (PWM) circuit 42, the output of which is connected by conductor 22 to the control terminal of switch S0. PWM circuit 42 controls the duty cycle of switch S0 in response to the output voltage generated by amplifier 17 so as to decrease the duty cycle of switch S0 as V_{BAT} gets closer to $V_{BAT(max)}$. PWM circuit 42 typically, but not always, is coupled to receive a clock signal (not shown) of a suitable frequency.

[0039] The described invention provides improved reliability of energy harvesting systems by providing simple, economical battery overcharge protection, and also by avoiding damage to inductors and/or other circuit components in power management circuits of the energy harvesting systems.

[0040] Embodiments having different combinations of one or more of the features or steps described in the context of example embodiments having all or just some of such features or steps are intended to be covered hereby. Those skilled in the art will appreciate that many other embodiments and variations are also possible within the scope of the claimed invention.

CLAIMS:

What is claimed is:

1. An energy harvesting system comprising:

an energy harvester for generating a harvested voltage;

an energy management circuit for converting the harvested voltage to an output voltage, the energy management circuit including an inductor having a first terminal coupled to receive the harvested voltage and a second terminal coupled to a first terminal of a first switch;

an energy storage device coupled to receive the output voltage; and

protection circuitry in the energy management circuit for shunting current generated by the energy harvester away from the energy storage device if the energy storage device is fully charged.

2. The energy harvesting system of claim 1, wherein the energy management circuit includes a control circuit coupled to a control terminal of the first switch.

3. The energy harvesting system of claim 2, wherein the energy management circuit includes a second switch coupled in parallel with the energy harvester to perform the shunting, the second switch having a control terminal coupled to the control circuit to control the shunting.

4. The energy harvesting system of claim 3, wherein a first terminal of the second switch is coupled to a first reference voltage, a second terminal of the second switch is coupled to a first terminal of a current-limiting resistor, and a second terminal of the current-limiting resistor is coupled to the first terminal of the inductor.

5. The energy harvesting system of claim 4, wherein the control circuit is coupled to receive the harvested voltage and the output voltage and operates to compare the output voltage to a maximum energy storage device reference voltage to determine whether the energy storage device is fully charged, and also operates to maintain the first switch open and the second switch closed to shunt the current generated by the energy harvester away from the inductor and the

energy storage device if the energy storage device is fully charged.

6. The energy harvesting system of claim 5, wherein the control circuit operates to compare the harvested voltage to the output voltage, maintain the second switch open, and operate the first switch so as to effectuate boosting of the harvested voltage by the energy management circuit if the harvested voltage is less than the output voltage.

7. The energy harvesting system of claim 6, wherein the control circuit operates to maintain the first and second switches open if the harvested voltage is less than the output voltage and the energy storage device is less than fully charged.

8. The energy harvesting system of claim 4, wherein the control circuit includes a comparator having a first input coupled to receive the harvested voltage, a second input coupled to receive a voltage indicating that the energy storage device is fully charged, and an output coupled to the control terminal of the second switch, and wherein the control circuit includes an amplifier having a first input coupled to receive the output voltage, a second input coupled to receive the maximum energy storage device reference voltage, and an output coupled by means of a pulse width modulation circuit to the control terminal of the first switch.

9. The energy harvesting system of claim 2, wherein the energy management circuit includes a second switch coupled in parallel with the first switch to perform the shunting, the second switch having a control terminal coupled to the control circuit to control the shunting, wherein a first terminal of the second switch is coupled to a first reference voltage and a second terminal of the second switch is coupled to the second terminal of the inductor.

10. The energy harvesting system of claim 9, wherein a current-limiting resistor couples the second terminal of the second switch to the second terminal of the inductor, and wherein the control circuit is coupled to receive the harvested voltage and the output voltage and operates to compare the output voltage to a maximum energy storage device reference voltage to determine whether the energy storage device is fully charged, and also operates to maintain the first switch open and the second switch closed to shunt the current generated by the energy

harvester away from the energy storage device if the energy storage device is fully charged.

11. The energy harvesting system of claim 10, wherein the control circuit operates to compare the harvested voltage to the output voltage, and maintains the second switch open and operates the first switch so as to effectuate boosting of the harvested voltage by the energy management circuit if the harvested voltage is less than the output voltage.

12. The energy harvesting system of claim 1, wherein the energy management circuit includes a rectifying element coupled between the second terminal of the inductor and the output voltage.

13. The energy harvesting system of claim 12, wherein the energy management circuit includes a boost converter.

14. A method for harvesting energy from an energy harvester to generate a harvested voltage, the method comprising:

converting the harvested voltage to an output voltage applied to an energy storage device by means of an energy management circuit including an inductor having a first terminal coupled to receive the harvested voltage and a second terminal coupled to a first terminal of a first switch;

transferring current generated by the energy harvester to the energy storage device by means of the energy management circuit if the energy storage device is not fully charged; and

shunting the current generated by the energy harvester away from the energy storage device to avoid overcharging the energy storage device if it is fully charged.

15. The method of claim 14, including shunting the current generated by the energy harvester away from the inductor.

16. The method of claim 15, wherein the step of shunting includes coupling the first terminal of the inductor through a current-limiting resistor and a second switch coupled in parallel with the energy harvester to a reference voltage.

17. The method of claim 15, wherein the step of shunting includes coupling a second terminal of the inductor through a current-limiting resistor and a second switch to a reference voltage.

18. The method of claim 15, including operating a control circuit to maintain the first switch open and the second switch closed if the harvested voltage is greater than the output voltage.

19. A system for harvesting energy from an energy harvester to generate a DC harvested voltage, the system comprising:

means for converting the harvested voltage to an output voltage applied to an energy storage device by means of an energy management circuit including an inductor having a first terminal coupled to receive the harvested voltage and a second terminal coupled to a first terminal of a first switch;

means for transferring current generated by the energy harvester to the energy storage device by means of the energy management circuit if the energy storage device is not fully charged; and

means for shunting the current generated by the energy harvester away from the energy storage device to avoid overcharging the energy storage device if it is fully charged.

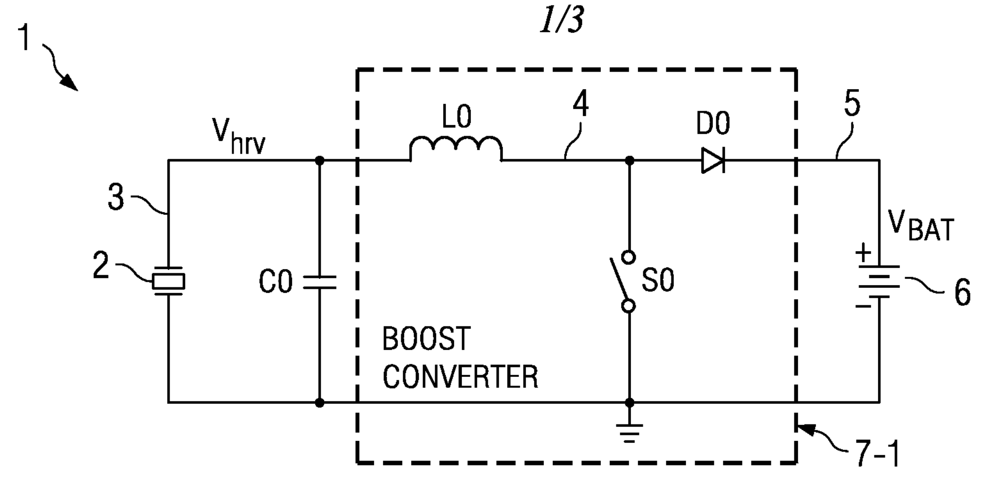

FIG. 1
(PRIOR ART)

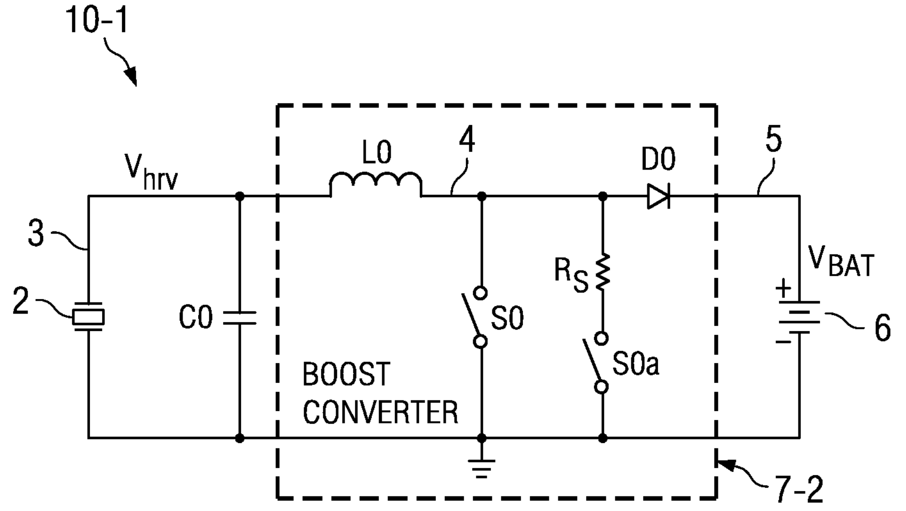

FIG. 2

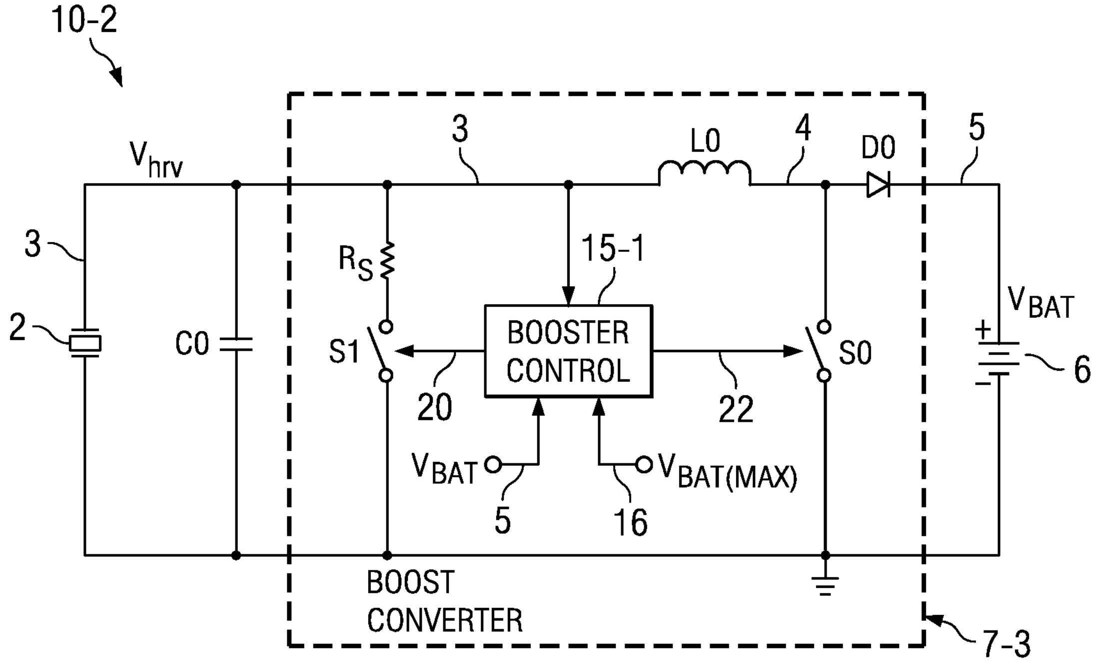

FIG. 3

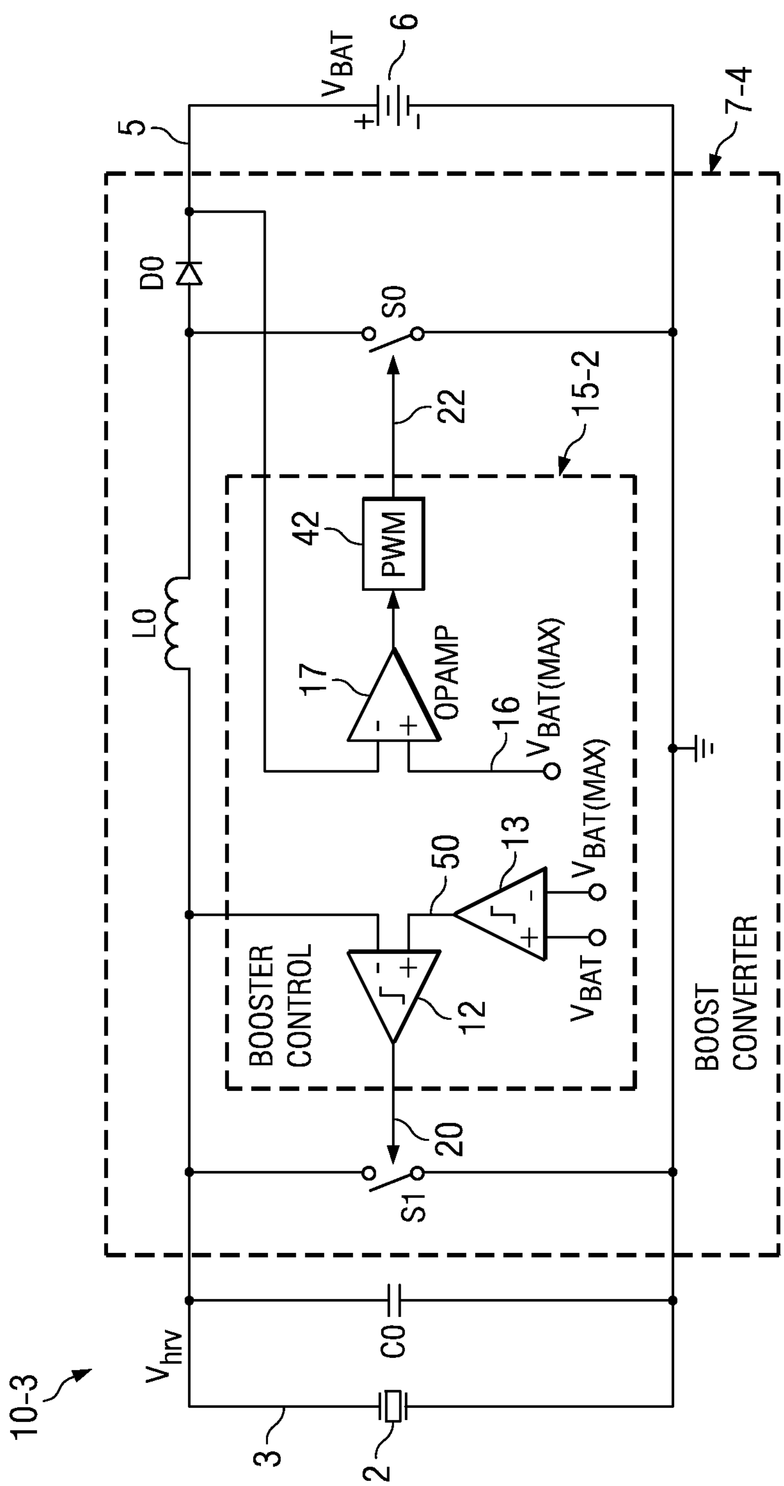
VBAT
6
5
7-4
D0
S0
15-2
22
42
PWM
L0
17
OPAMP
16
VBAT(MAX)
50
13
VBAT(MAX)
BOOSTER
CONTROL
12
VBAT
BOOST
CONVERTER
20
S1
C0
Vhrv
10-3
3
2

FIG. 4

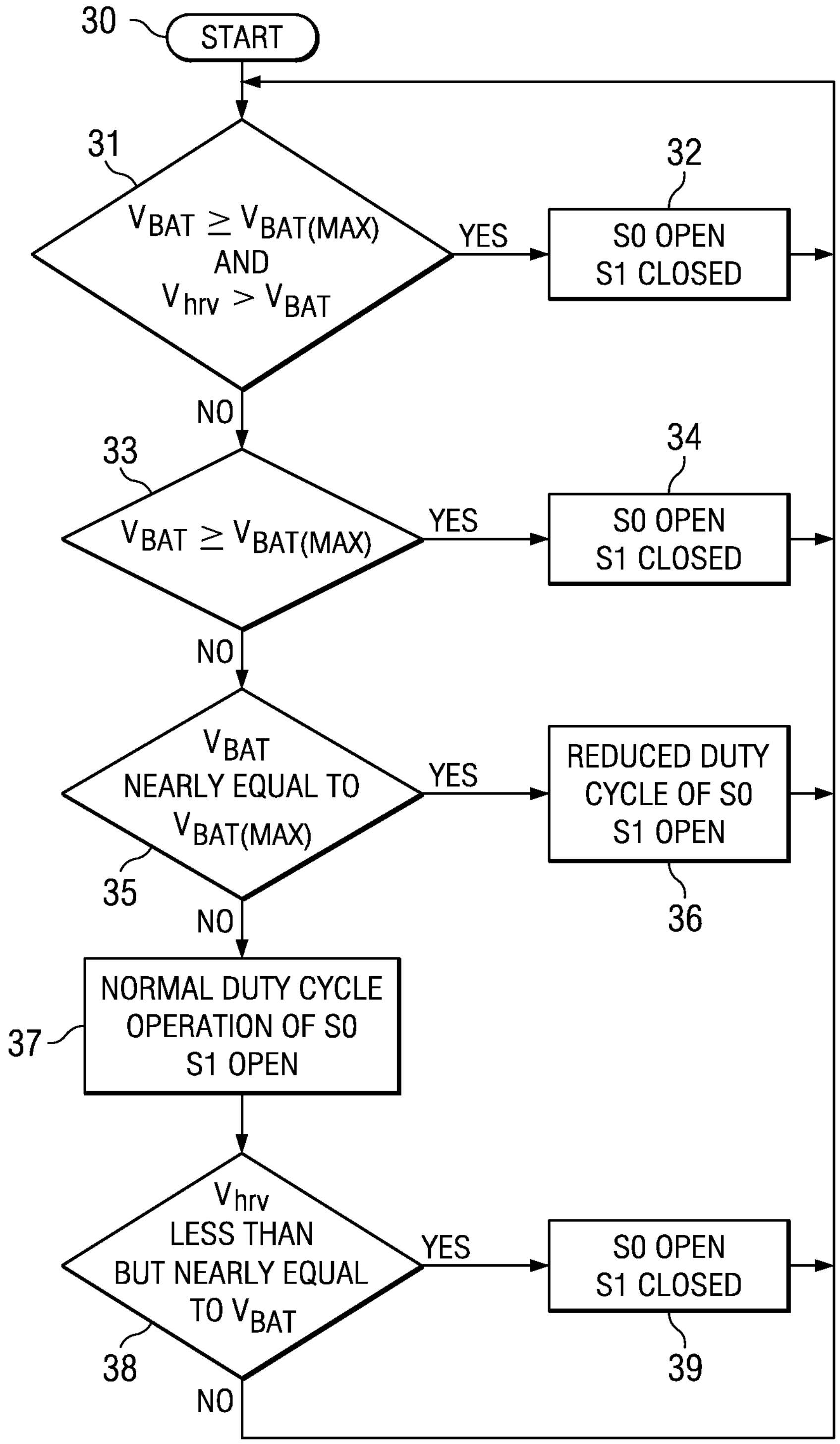
30
START
31
V_BAT ≥ V_BAT(MAX)
AND
V_hrv > V_BAT
YES
32
S0 OPEN
S1 CLOSED
NO
33
V_BAT ≥ V_BAT(MAX)
YES
34
S0 OPEN
S1 CLOSED
NO
V_BAT
NEARLY EQUAL TO
V_BAT(MAX)
35
YES
REDUCED DUTY
CYCLE OF S0
S1 OPEN
36
NO
37
NORMAL DUTY CYCLE
OPERATION OF S0
S1 OPEN
V_hrv
LESS THAN
BUT NEARLY EQUAL
TO V_BAT
38
YES
S0 OPEN
S1 CLOSED
39
NO

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2010/061831

A. CLASSIFICATION OF SUBJECT MATTER

H02J 7/00(2006.01)i, H02H 7/18(2006.01)i, H02M 3/155(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02J 7/00; H02J 7/34; G05F 1/00; H02J 7/04; H01M 10/48; H01M 10/46; B60L 1/00

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: energy harvester, switch, protection, converter, inductor, resistor, battery

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6239584 B1 (JANG; YUNGTAEK et al.) 29 May 2001 See the abstract; claim 1; figures 6-7, 10, 12.	1-19
A	US 2009-0206657 A1 (VUK IVAN et al.) 20 August 2009 See the abstract; claim 1; figures 1-3, 6.	1-19
A	US 2009-0251099 A1 (BRANTNER PAUL C. et al.) 08 October 2009 See the abstract; claim 1; figures 1, 10.	1-19
A	US 2009-0309538 A1 (XU JIAN) 17 December 2009 See the abstract; claim 1; figure 1.	1-19
A	US 2008-0048620 A1 (WEI ZHANG) 28 February 2008 See the abstract; claim 1; figure 1.	1-19

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

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

Date of the actual completion of the international search	Date of mailing of the international search report
13 JUNE 2011 (13.06.2011)	**15 JUNE 2011 (15.06.2011)**

Name and mailing address of the ISA/KR	Authorized officer
Korean Intellectual Property Office Government Complex-Daejeon, 189 Cheongsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea	WEE Jae Woo
Facsimile No. 82-42-472-7140	Telephone No. 82-42-481-8540

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2010/061831

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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US 2009-0206657 A1	20.08.2009	EP 2091055 A2	19.08.2009
		US 7786620 B2	31.08.2010
US 2009-0251099 A1	08.10.2009	None	
US 2009-0309538 A1	17.12.2009	None	
US 2008-0048620 A1	28.02.2008	CN 101132136 A	27.02.2008
		JP 2008-079491 A	03.04.2008
		KR 10-2008-0018825 A	28.02.2008
		TW 200832861 A	01.08.2008
		US 7855531 B2	21.12.2010