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(54) Title: ENERGY HARVESTER BATTERY CHARGER CIRCUIT AND METHOD

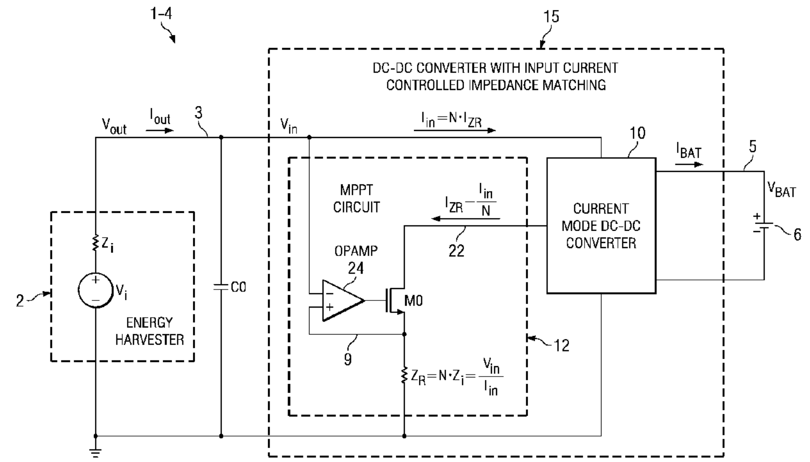

FIG. 4

(57) Abstract: An energy harvesting system for transferring energy from an energy harvester (2) having an output impedance (Z_i) to a DC-DC converter (10) includes a maximum power point tracking (MPPT) circuit (12) including a replica impedance (Z_R) which is a multiple (N) of the output impedance. The MPPT circuit applies a voltage across the replica impedance that is equal to an output voltage (V_{in}) of the harvester to generate a feedback current (I_{ZR}) which is equal to an input current (I_{in}) received from the harvester, divided by the multiple (N), to provide maximum power point tracking between the harvester and the converter.

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ENERGY HARVESTER BATTERY CHARGER CIRCUIT AND METHOD

[0001] This relates generally to energy harvesting and, more particularly, to circuits and methods for improving the efficiency of transferring energy from energy harvesting devices to energy storage devices and/or load devices.

BACKGROUND

[0002] Recently, various very low power integrated circuits that require extremely low amounts of operating current (often referred to as "nanopower" integrated circuits) 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. The harvested power then usually is 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 microamp.)

[0003] FIG. 1 shows an energy harvesting system 1-1 in which the output of a thermopile energy harvester 2-1 is coupled by a DC-DC converter (i.e., battery charger) 10 to a battery or supercapacitor 6, hereinafter referred to simply as battery 6. Thermopile energy harvester 2-1 can be modeled as a voltage source V_T coupled between ground and one terminal 3A of a resistor R_i. Resistor R_i represents the internal thermopile resistance. An internal capacitance C_T is coupled between conductor 3A and ground. (The internal resistance of typical commercially available thermopile harvesters may be from about 300 ohms to 1 kilohm.) The output of thermopile energy harvester 2-1 applies an output voltage V_{out} via conductor 3 to the input of DC-DC-converter 10, thereby supplying an output current I_{out} into DC-DC converter 10, which charges battery 6.

[0004] It can be readily shown that the transfer of power from thermopile energy harvester 2-1 is optimized if the thermopile harvester output resistance is equal to the equivalent input resistance V_{in}/I_{in} of DC-DC converter 10. The input impedance V_{in}/I_{in} of a typical boost, buck, or buck/boost converter or battery charger 10 typically does not have a fixed value, because DC-DC converter 10 operates so as to draw as much input current I_{in} from its input as battery 6 can accept.

[0005] FIG. 2 shows another energy harvesting system 1- 2 in which the output of an induction harvester 2-2 is coupled by DC-DC converter 10 to battery 6. Induction harvester 2-2 can be modeled as an EMF (electromotive force) voltage source ε_L coupled in series with inductances L_{FB} and L_{coil} and coil resistance R_{coil}.(The internal resistance R_{coil} of typical commercially available induction harvesters may be from about 1 ohm to 10 kilohms.) For optimum power transfer it is necessary to match the input impedance of DC-DC converter 10 to the output impedance of induction harvester 2-2.

[0006] FIG. 3 shows yet another energy harvesting system 1- 3 in which the output of photo-voltaic solar cell 2-3 is coupled by a DC-DC converter 10 to battery 6. Solar cell harvester 2-3 can be modeled as a current source I_{PH} coupled between conductor 3A and ground in parallel with diode D and leakage resistance R_P. A series resistance R_S (which typically may be from about 0.1 to 100 ohms) is connected between conductor 3A and harvester output conductor 3. For optimum power transfer it is necessary to match the input impedance of the DC-DC converter to the equivalent output impedance of solar cell harvester 2-3.

[0007] The I_{out}/P_{out} versus V_{out} curve in FIG. 3 indicates that if V_{out} is held above the turn-on threshold voltage of diode D, then all of the current I_{out} generated by solar harvester 2-3 flows through diode D to ground. Therefore, if the value of V_{out} is too high, the current generated by solar harvester 2-3 is wasted. Initially, P_{out} increases linearly with respect to V_{out} because the generated current I_{out} by the current source I_{PH} in FIG. 3 is constant. As the generated current starts to flow through diode D, a maximum or peak value occurs in the P_{out} curve. Thus, if the value of V_{out} is too low, the full amount of available harvested power ($V_{out} \times I_{out}$) is not being made available at the output of solar cell harvester 2-3, and if the value of V_{out} is high enough that some or all of the generated current I_{PH} is flowing through diode D to ground, then the corresponding power is wasted and cannot be converted into a suitable output voltage and output current for charging battery 6.

[0008] The amount of power available from the harvesters of FIGS. 1-3 usually is small and unpredictable, so the intermediate energy storage (e.g., lithium batteries or super capacitors) is often required in these applications to provide for system power needs when energy from the harvester is unavailable or insufficient. It is important that the small amounts of power available from nanopower harvesting devices be "managed" so that the harvested energy is transferred as efficiently as possible, with minimum power loss, to charge batteries or energize utilization devices.

[0009] Well-known impedance matching techniques to optimize transfer of power from the output of a first circuit to the input of a second circuit involve matching the output impedance of the first circuit to the input impedance of the second circuit.

[0010] A common technique for optimizing the efficiency of harvesting power from large P-V (photo-voltaic) solar cells (which generate large amounts of power) is managed in order to charge batteries and/or energize utilization devices is referred to as "maximum power point tracking" (MPPT). Such MPPT optimization utilizes a digital processor to control the amount of power being harvested by executing various known complex MPPT algorithms to adjust the voltage values and current values of the DC-DC converter 10 so as to derive a "maximum power point". Normally, MPPT tracking is performed by using a digital algorithm to adjust the input current I_{in} delivered from the harvester to the input of the DC-DC converter and determining or measuring the amount of power delivered to the input of the DC-DC converter.

[0011] For example, the MPPT algorithm might decrease the amount of current I_{in}, which might cause the amount of power transferred to decrease. Or, the MPPT algorithm might repeatedly increase the amount of current I_{in}, which might cause the amount of power transferred to repeatedly increase, until at some point the amount of power transferred starts to decrease instead of increasing. This would mean that the point of a maximum efficiency power transfer, i.e., the maximum power point, under the present circumstances has been determined. The MPPT algorithm typically would operate so as to maintain the optimum efficiency balance between the input current I_{in} delivered to the input of the DC-DC converter and the resulting input voltage V_{in} of the DC-DC converter.

[0012] Unfortunately, such prior complex digital MPPT power optimization algorithms consume too much energy to be applicable in nanopower harvesting applications. Various patents, including US Patent Nos. 7,564,013 and 7,394,237 , disclose known MPPT power optimization techniques.

SUMMARY

[0013] In accordance with an example embodiment, the invention provides an energy harvesting system for transferring energy from an energy harvester (2) having an output impedance (Z_i) to a DC-DC converter (10). A maximum power point tracking (MPPT) circuit (12) includes a replica impedance (Z_R) which is a multiple (N) of the harvester output impedance. The MPPT circuit (12) applies a voltage equal to an output voltage (V_{in}) of the harvester across the replica impedance (Z_R) to generate a feedback current (I_{ZR}) which is equal to an input current (I_{in}) received from the harvester (2), divided by the multiple (N), to provide maximum power point tracking between the harvester (2) and the DC-DC converter (10).

[0014] In an example embodiment, the invention provides an energy harvesting system (1-4,5, 6) including an energy harvester (2) having an output impedance (Z_i) and a first DC-DC converter (15) for converting an input voltage (V_{in}) received from an output conductor (3) of the energy harvester (2) to an output signal (I_{BAT}, V_{BAT}). The first DC-DC converter (15) has an input impedance ($V_{in} \div I_{in}$) controlled by the input voltage (V_{in}) to match the output impedance (Z_i) so as to provide maximum power point tracking (MPPT) between the energy harvester (2) and the first DC-DC converter (15). A receiving device (6) is coupled to receive the output signal (I_{BAT}, V_{BAT}). In a described embodiment, the first DC-DC converter (15) includes a second DC-DC converter (10) having a first input coupled to the output conductor (3) of the energy harvester (2) and a second input coupled to a reference voltage (GND). The first DC-DC converter (15) also includes a MPPT (maximum power point tracking) circuit (12) coupled between the output conductor (3) of the energy harvester (2) and the reference voltage (GND).

[0015] In an example embodiment, the MPPT circuit (12) includes a replica impedance (Z_R) coupled between the output conductor (3) of the energy harvester (2) and the reference voltage (GND). The replica impedance (Z_R) has a value which is a predetermined multiple (N) of the harvester output impedance (Z_i), wherein a feedback or replica current (I_{ZR}) flows through the replica impedance (Z_R). The replica current (I_{ZR}) is equal to the input current (I_{in}) divided by the predetermined multiple (N). In a described embodiment, the predetermined multiple (N) is approximately 4000.

[0016] In an example embodiment, the MPPT circuit (12) includes a transistor (M0) coupled between a conductor (28) and the replica impedance (Z_R). The replica current (I_{ZR}) flows through the conductor (28). The MPPT circuit (12) also includes an amplifier (24) having a first input (-) coupled to the output conductor (3) of the energy harvester (2), an output coupled to a control electrode of the transistor (M0), and a second input (+) coupled to a junction (9) between the transistor (M0) and the replica impedance (Z_R).

[0017] In an example embodiment, the second DC-DC converter (10) includes an inductor

(L0) having a first terminal (3-1) coupled to the output conductor (3) of the energy harvester (2) and a second terminal (4) coupled to a first terminal of a switch (S0) and to an anode terminal of a rectifier (D0). A second terminal of the switch (S0) is coupled to the reference voltage (GND).

[0018] In an example embodiment, the second DC-DC converter (10) includes a PWM (pulse width modulator) circuit (20) having an output coupled to a control terminal of the switch (S0) and an input (27) coupled to the conductor (28), and the MPPT circuit (12) includes a current sensor (13) having a first current-conducting terminal connected to the output terminal (3) of the energy harvester (2), a second current-conducting terminal connected to the first terminal (3-1) of the inductor (L0), and an output coupled by means of a current summing circuit (23) to the conductor (28). The replica current (I_{ZR}) is compared to an inductor current sensed by the current sensor (13) and wherein the PWM circuit (20) accordingly controls the duty cycle of the switch (S0) so as to maintain the replica current (I_{ZR}) equal to the input current (I_{in}) divided by the predetermined multiple (N). The amplifier (24) operates to maintain a voltage across the replica impedance (Z_R) equal to the a voltage (V_{in}) on the output conductor (3) of the energy harvester (2).

[0019] In an example embodiment, a processor (30) is coupled to the replica impedance (Z_R) to provide predetermined adjustments to the value of the replica impedance (Z_R) at predetermined times, respectively.

[0020] In an example embodiment, the invention provides a method for optimizing the efficiency of transferring energy to a second DC-DC converter (10), including applying an output current (I_{out}) generated by an energy harvester (2) having an output impedance (Z_i) as an input current (I_{in}) to a second DC-DC converter (10); providing a replica impedance (Z_R) which is a scaled replica of the output impedance (Z_i) equal to the output impedance (Z_i) multiplied by a predetermined multiple (N); applying an output voltage (V_{in}) received from an output conductor (3) of the energy harvester (2) across the replica impedance (Z_R) to generate a feedback current (I_{ZR}) representative of the input current (I_{in}) supplied by the energy harvester (2) to the second DC-DC converter, the feedback current (I_{ZR}) flowing to the replica impedance (Z_R) being derived from the input current (I_{in}) to provide maximum power point tracking (MPPT) between the energy harvester (2) and the second DC-DC converter (10); and applying an output signal (V_{BAT}) generated by the second DC-DC converter (10) to a receiving device (6).

[0021] In an example embodiment, the method includes applying the output voltage (V_{in}) received from the output conductor (3) of the energy harvester (2) across the replica impedance

(Z_R) by means of an operational amplifier (24) having a first input (-) coupled to the output conductor (3) of the energy harvester (2), an output coupled to a control electrode of a transistor (M0) coupled between the output conductor (3) of the energy harvester (2), and a second input (+) coupled to a junction (9) between the transistor (M0) and the replica impedance (Z_R). In one embodiment, the second DC-DC converter (10) includes an inductor (L0) having a first terminal (3-1) coupled to the output conductor (3) of the energy harvester (2) and a second terminal (4) coupled to a first terminal of a switch (S0) and to an anode terminal of a rectifier (D0), a second terminal of the switch (S0) being coupled to the reference voltage (GND), the method including coupling an input of a PWM circuit (20) to the conductor (28) and coupling an output coupled off the PWM circuit (20) to a control terminal of the switch (S0).

[0022] In an example embodiment, the method includes comparing the feedback current (I_{ZR}) is compared to a current in the inductor (L0) and operating the PWM circuit (20) to control the duty cycle of the switch (S0) so as to maintain the feedback current (I_{ZR}) equal to the input current (I_{in}) divided by the predetermined multiple (N).

[0023] In an example embodiment, the method includes providing the replica resistance (Z_R) with a value that is approximately 4000 times greater than the value of the output impedance (Z_i).

[0024] In an example embodiment, the invention provides an energy harvesting system for optimizing the efficiency of transferring energy to a DC-DC converter (10), including means (3, 13) for applying an output current (I_{out}) generated by an energy harvester (2) having an output impedance (Z_i) as an input current (I_{in}) to the DC-DC converter (10); replica impedance means (Z_R) for providing a replica impedance (Z_R) which is a scaled representation of the output impedance (Z_i); means (24, M0) for applying an output voltage (V_{in}) received from an output conductor (3) of the energy harvester (2) across the replica impedance (Z_R) to generate a feedback current (I_{ZR}) representative of the input current (I_{in}) supplied by the energy harvester (2) to the DC-DC converter, the replica feedback current (I_{ZR}) flowing to the impedance (Z_R) being derived from the output conductor (3) of the energy harvester (2) to provide maximum power point tracking (MPPT) between the energy harvester (2) and the DC-DC converter (10); and means (5) for applying an output signal (V_{BAT}) generated by the DC-DC converter (10) to a receiving device (6).

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] Example embodiments are described with reference to accompanying drawings, wherein:

[0026] FIG. 1 is a schematic diagram of an equivalent circuit of a thermopile energy harvester coupled to a battery by means a power management circuit.

[0027] FIG. 2 is a schematic diagram of an induction harvester equivalent circuit coupled to a battery by means of a power management circuit.

[0028] FIG. 3 is a schematic diagram of a solar cell harvester equivalent circuit coupled to a battery by means of a power management circuit.

[0029] FIG. 4 is a block diagram of an energy harvester coupled to a maximum power point tracking circuit associated with a DC-DC converter coupled between the energy and a battery.

[0030] FIG. 5 is a schematic diagram of a more detailed implementation of the circuit shown in FIG. 4.

[0031] FIG. 6 is a block diagram illustrating use of a processor to periodically adjust the replica impedance Z_R in FIGS. 4 and 5.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0032] FIG. 4 shows an energy harvesting system 1-4 in which the output of energy harvester 2 is coupled by a DC-DC converter or battery charger 15 to battery 6. DC-DC converter 15 delivers a current I_{BAT} and corresponding voltage V_{BAT} to battery 6 via conductor 52. Energy harvester 2 is modeled as a voltage source V_i coupled between ground and one terminal of an internal impedance Z_i of energy harvester 2. The other terminal of internal impedance Z_i is connected by conductor 3 to the output of harvester 2, on which a harvester output voltage V_{out} is generated. A harvester output current I_{out} flows through conductor 3. The output 3 of energy harvester 2 is connected to the input of DC-DC converter 15 and applies an output voltage V_{in} via conductor 3 to the input of DC-DC converter 15 and also supplies an input current I_{in} to DC-DC converter 15. Thus, the output voltage V_{out} and output current I_{out} generated by harvester 2 are equal to the input voltage V_{in} and input current I_{in}, respectively, of DC-Dc converter 15. DC-DC converter 15 charges battery 6 via output conductor 5.

[0033] DC-DC converter 15 in FIG. 4 is a DC-DC converter having a controlled-input impedance equal to $V_{in} \div I_{in}$. DC-DC converter 15 includes a conventional DC-DC converter 10 and a MPPT (maximum power point tracking) circuit 12. Two inputs of DC-DC converter 10 are connected to conductor 3 and ground, respectively. DC-DC converter 10 provides a “replica” feedback current I_{ZR} which controls the input current I_{in} (e.g., the inductor current in inductor L0 of FIG. 5) in DC-DC converter 10 so as to make I_{in} proportional to feedback current I_{ZR}.

[0034] MPPT circuit 12 of DC-DC converter 15 includes an operational amplifier 24 having its (-) input connected to conductor 3 and its output connected to the gate of a N-channel transistor M0. The drain of transistor M0 is connected by conductor 22 to a feedback terminal of DC-DC converter 10 and conducts feedback current I_{ZR} into the drain of transistor M0. The source of transistor M0 is connected by conductor 9 to one terminal of a “replica” impedance Z_R and to the (+) input of amplifier 24. The other terminal of replica impedance Z_R is connected to ground. Replica impedance Z_R is a scaled (by a factor of N) replica of output impedance Z_i of energy harvester 2.

[0035] A feedback loop including conductor 22, transistor M0, amplifier 24, and replica impedance Z_R operates to keep the voltage across replica impedance Z_R equal to input voltage V_{in}. V_{in} varies according to how much power or input current I_{in} is presently being generated by harvester 2. The value of feedback current I_{ZR} is determined by the value of replica impedance $Z_R=N\times Z_i=V_{in}\div I_{in}$. The operation of DC-DC converter 15 is such that replica impedance Z_R is equal to $V_{in}\div I_{in}$, which is the effective input impedance of DC-DC converter 15. Therefore, replica current I_{ZR}, which flows to ground through the feedback impedance $Z_R=N\times Z_i=V_{in}\div I_{in}$, is equal to I_{in}/N. The multiple N may have a relatively high value, e.g., 4000. DC-DC converter 15 appears to energy harvester 2 as replica impedance $Z_R= N\times Z_i=V_{in}\div I_{in}$ and therefore is considered to be matched to the harvester output impedance Z_i. (Since the current I_{in} flows through output impedance Z_i of energy harvester 2, and since replica current $I_{ZR} = I_{in}/N$ flows through replica impedance $Z_R =N\times Z_i$, the resulting voltage drop across harvester output impedance Z_i is equal to the resulting voltage drop across replica impedance $Z_R =N\times Z_i$, so harvester output impedance Z_i is matched to the input impedance $Z_R=N\times Z_i=V_{in}\div I_{in}$.)

[0036] Feedback current I_{ZR} tracks changes in input voltage V_{in}, and this is what keeps replica impedance Z_R and input impedance V_{in}/I_{in} approximately matched to harvester output impedance Z_i. As an example, if replica impedance Z_R is equal to 1 megohm and the multiple or scale factor N is equal to 4000, then DC-DC converter 15 will appear to harvester 2 as a 250 ohm resistor.

[0037] Thus, energy harvester system 1-4 in FIG. 4 provides a way to control the effective input impedance $V_{in}÷I_{in}$ of DC-DC converter 15 by causing the effective input impedance $V_{in}÷I_{in}$ to match the output impedance of energy harvester 2. This is accomplished by using input voltage V_{in} of the DC-DC converter 15 to generate feedback current I_{ZR}, for example by means of replica impedance Z_R. Replica impedance Z_R can be provided by means of a suitable resistor or diode or other component which roughly matches the output impedance of a particular energy harvester 2. DC-DC converter 10 is configured in such a way that it provides feedback current I_{ZR} so as to determine the input current I_{in} of DC-DC converter 15 such that effective input impedance $Z_R=N\times Z_i=V_{in}÷I_{in}$. appears to the output of harvester 2 as the matched replica impedance Z_R.

[0038] Energy harvesting system 1-5 of FIG. 5 includes a more detailed implementation of DC-DC converter 15. DC-DC converter 10 in FIG. 5 includes inductor L0 with one terminal connected to one current-conducting terminal 3-1 of a current sensor circuit 13. (One way current sensor circuit 13 can be implemented is indicated in FIG. 1 of commonly assigned US Patent 6,377,034 entitled “Method and Circuits for Inductor Current Measurement in MOS Switching Regulators” issued to Ivanov on April 23, 2002, which is incorporated herein by reference.) The other terminal of inductor L0 is connected by conductor 4 to one terminal of switch S0 and to the “anode” terminal of a synchronous rectifier circuit or diode D0. The cathode of diode D0 is connected by conductor 5 to the (+) terminal of battery 6. DC-DC converter 15 delivers a current I_{BAT} and corresponding voltage V_{BAT} to battery 6 via conductor 52.

[0039] The other terminal of switch S0 is connected to ground. The control terminal of switch S0 is connected to the output 29 of a conventional pulse width modulator (PWM) circuit 20. The input of PWM circuit 20 is connected by conductor 27 to an output of a conventional current summing circuit 23. An input of current summing circuit 23 is connected by conductor 22 to the output of current sensor circuit 13. Another output of current summing circuit 23 is connected by conductor 28 to the drain of transistor M0. The other current-conducting terminal of current sensor 13 is connected to conductor 3.

[0040] Operational amplifier 24 maintains the voltage across replica resistor or impedance Z_R equal to V_{in} (as in FIG. 4). The output of current sensor circuit 13 is the feedback current I_{ZR} which flows through transistor M0 and replica impedance Z_R. The feedback current I_{ZR} controls the input current I_{in} of DC-DC converter 15. As in FIG. 4, the equivalent input impedance $V_{in}÷I_{in}$ of DC-DC converter 15 in FIG. 5 is equal to Z_R multiplied by the current sensor ratio N, which is equal to I_{in}/I_{ZR}. The feedback current I_{ZR} is compared to the sensed inductor current I_{in}. This comparison of I_{ZR} to the sensed inductor current I_{in} is accomplished by causing I_{in} and I_{ZR} to flow in opposed directions into a connection point that is loaded by an impedance, such as a filtering capacitance or a resistance. The difference between the two currents develops a corresponding difference voltage across the impedance, and that difference voltage is applied to the input of PWM circuit 20. PWM circuit 20 accordingly controls the duty cycle of switch S0 so as to maintain I_{ZR} equal to I_{in}/N. (PWM circuit 20 typically can include an oscillator and a few other circuit elements, but it can be just a hysteretic comparator in a self-oscillating loop.) In any case, the resulting limiting of the feedback current $I_{FB}=I_{ZR}$ effectively limits the current I_{in} through inductor L0.

[0041] It should be appreciated that the above described MPPT circuit 12 is useful for micropower applications such as portable energy harvesters. However, MPPT circuit 12 has a fixed replica impedance $Z_R = N \times Z_i$, but using a fixed value of replica impedance Z_R may not be suitable for certain energy harvesters in which the internal harvester impedance (i.e., the harvester output impedance) Z_i can vary significantly over temperature, time and/or operating conditions. For example, in certain applications, such as large-scale solar power harvesting systems or automotive thermal harvester devices attached to a high-temperature engine or exhaust pipe, wherein relatively large amounts of harvested power are generated, the above described MPPT technique can be further optimized by making the replica impedance Z_R occasionally or periodically adjustable.

[0042] As shown in FIG. 6, this can be accomplished by utilizing a system processor 30 to adjust the value of Z_R based on the amount of power being generated, in accordance with various known MPPT algorithms. Such Z_R adjustments can be performed relatively infrequently, triggered, for example, by timekeeping devices or significant environmental changes. This technique can save computational system resources and can substantially reduce the amount of power consumed by the MPPT process.

[0043] The described MPPT system controls the converter input current I_{in} in inductor L0 as a function of the input voltage V_{in} applied by harvester 2 to the input of DC-DC converter 15 and provides effective matching of the harvester output impedance Z_i to the input impedance V_{in}/I_{in} of DC-DC converter 15, by providing a replica of the harvester output impedance Z_i and biasing it with the output voltage of harvester 2 to determine the input impedance $V_{in} \div I_{in}$ of converter 15. This effectively optimizes transfer of power from harvester 2 to DC-DC converter 15 and produces a simple, economical MPPT circuit and technique for nanopower energy harvesting applications.

[0044] 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 having an output impedance;

a first DC-DC converter for converting an input voltage received from an output conductor of the energy harvester to an output signal, the first DC-DC converter having an input impedance controlled by the input voltage to match the output impedance so as to provide maximum power point tracking (MPPT) between the energy harvester and the first DC-DC converter; and

a receiving device coupled to receive the output signal.

2. The energy harvesting system of claim 1, wherein the receiving device includes a battery.

3. The energy harvesting system of claim 2, wherein the first DC-DC converter includes a second DC-DC converter having a first input coupled to the output conductor of the energy harvester and a second input coupled to a reference voltage, and wherein the first DC-DC converter also includes a MPPT (maximum power point tracking) circuit coupled between the output conductor of the energy harvester and the reference voltage.

4. The energy harvesting system of claim 3, wherein the MPPT circuit includes a replica impedance coupled between the output conductor of the energy harvester and the reference voltage, the replica impedance having a value which is a predetermined multiple of the harvester output impedance, wherein a feedback current flows through the replica impedance.

5. The energy harvesting system of claim 4, wherein the feedback current is equal to the input current divided by the predetermined multiple.

6. The energy harvesting system of claim 4, wherein the predetermined multiple is approximately 4000.

7. The energy harvesting system of claim 4, wherein the MPPT circuit includes a transistor coupled between a conductor and the replica impedance, and wherein the feedback current flows through the conductor, and wherein the MPPT circuit also includes an amplifier having a first input coupled to the output conductor of the energy harvester, an output coupled to a control electrode of the transistor, and a second input coupled to a junction between the transistor and the replica impedance.

8. The energy harvesting system of claim 7, wherein the second DC-DC converter includes an inductor having a first terminal coupled to the output conductor of the energy harvester and a second terminal coupled to a first terminal of a switch and to an anode terminal of a rectifier, a second terminal of the switch being coupled to the reference voltage.

9. The energy harvesting system of claim 8, wherein the second DC-DC converter includes a PWM (pulse width modulator) circuit having an output coupled to a control terminal of the switch and an input coupled to the conductor.

10. The energy harvesting system of claim 9, wherein the MPPT circuit includes a current sensor having a first current-conducting terminal connected to the output terminal of the energy harvester, a second current-conducting terminal connected to the first terminal of the inductor, and an output coupled to the conductor.

11. The energy harvesting system of claim 10, wherein the feedback current is compared to an inductor current sensed by the current sensor and wherein the PWM circuit accordingly controls the duty cycle of the switch so as to maintain the feedback current equal to the input current divided by the predetermined multiple.

12. The energy harvesting system of claim 7, wherein the amplifier operates to maintain a voltage across the replica impedance equal to the voltage on the output conductor of the energy harvester .

13. The energy harvesting system of claim 4, including a processor coupled to the replica impedance to provide predetermined adjustments to the value of the replica impedance at predetermined times, respectively.

14. The energy harvesting system of claim 1, wherein the energy harvester is an energy harvester selected from the group including a vibration energy harvester, a photovoltaic solar cell energy harvester, and a thermal energy harvester.

15. A method for optimizing the efficiency of transferring energy to a DC-DC converter, the method comprising:

applying an output current generated by an energy harvester having an output impedance as an input current to the DC-DC converter;

providing a replica impedance which is a scaled replica of the output impedance equal to the output impedance multiplied by a predetermined multiple;

applying an output voltage received from an output conductor of the energy harvester across the replica impedance to generate a feedback current representative of the input current supplied by the energy harvester to the DC-DC converter, the feedback current flowing to the replica impedance being derived from the input current to provide maximum power point tracking (MPPT) between the energy harvester and the DC-DC converter; and

applying an output signal generated by the DC-DC converter to a receiving device.

16. The method of claim 15, wherein the step of applying an output voltage includes applying the output voltage received from the output conductor of the energy harvester across the replica impedance by means of an operational amplifier having a first input coupled to the output conductor of the energy harvester, an output coupled to a control electrode of a transistor coupled between the output conductor of the energy harvester, and a second input of the operational amplifier coupled to a junction between the transistor and the replica impedance.

17. The method of claim 15, wherein the step of applying a replica resistance includes providing the replica resistance with a value that is approximately 4000 times greater than the value of the output impedance.

18. The method of claim 16, wherein the DC-DC converter includes an inductor having a first terminal coupled to the output conductor of the energy harvester and a second terminal coupled to a first terminal of a switch and to an anode terminal of a rectifier, a second terminal of the switch being coupled to the reference voltage, the method including coupling the conductor to an input of a pulse width modulated (PWM) circuit and coupling an output of the PWM circuit to a control terminal of the switch.

19. The method of claim 18, including comparing the feedback current is compared to a current in the inductor and operating the PWM circuit to control the duty cycle of the switch so as to maintain the feedback current equal to the input current divided by the predetermined multiple.

20. An energy harvesting system for optimizing the efficiency of transferring energy to a DC-DC converter, comprising:

means for applying an output current generated by an energy harvester having an output impedance as an input current to the DC-DC converter;

replica impedance means for providing a replica impedance which is a scaled representation of the output impedance;

means for applying an output voltage received from an output conductor of the energy harvester across the replica impedance to generate a feedback current representative of the input current supplied by the energy harvester to the DC-DC converter, the feedback current flowing to the replica impedance being derived from the input current to provide maximum power point tracking (MPPT) between the energy harvester and the DC-DC converter; and

means for applying an output signal generated by the DC-DC converter to a receiving device.

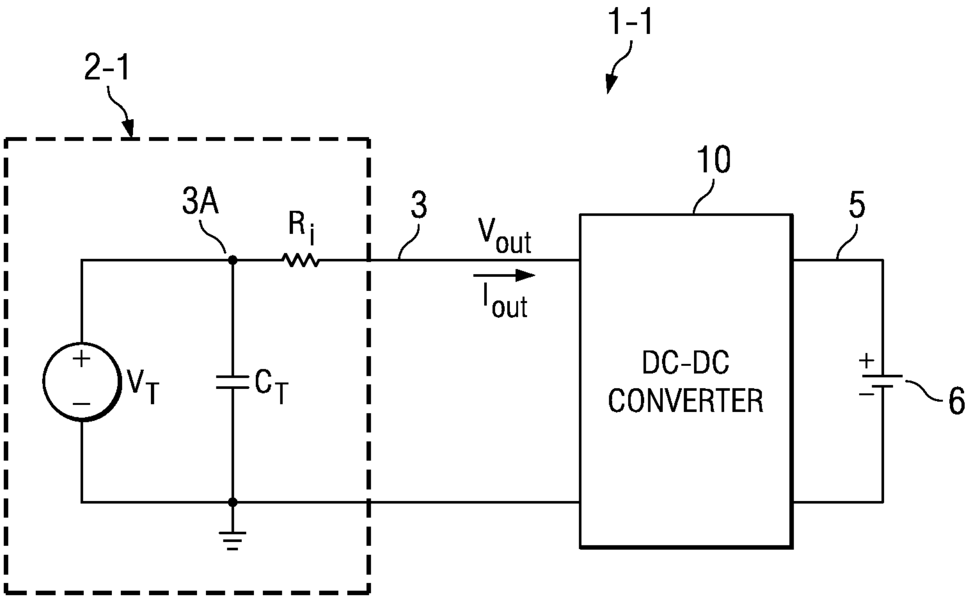


FIG. 1
(PRIOR ART)

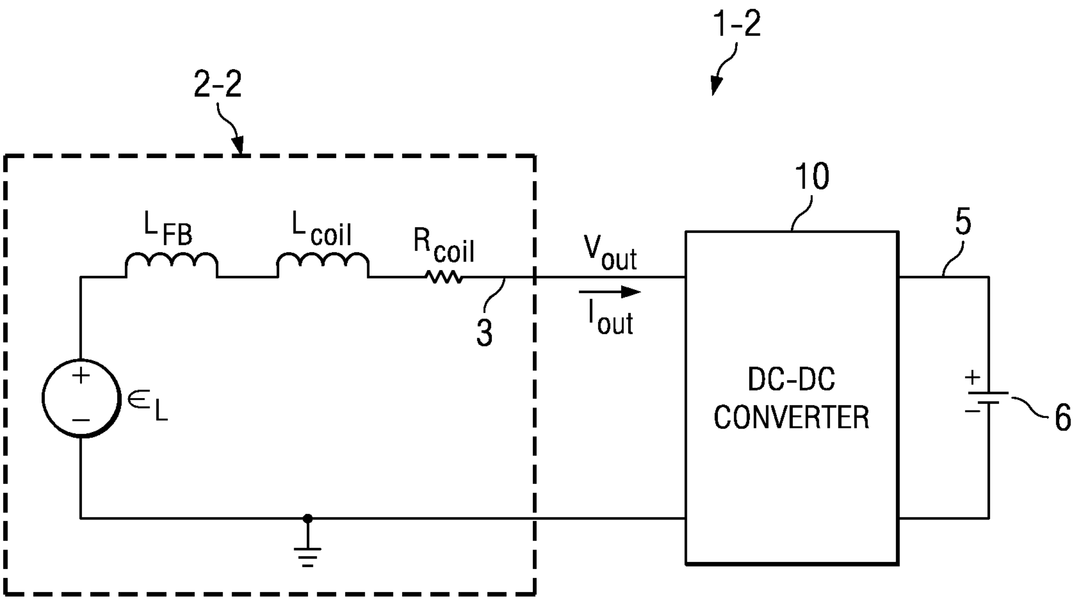


FIG. 2
(PRIOR ART)

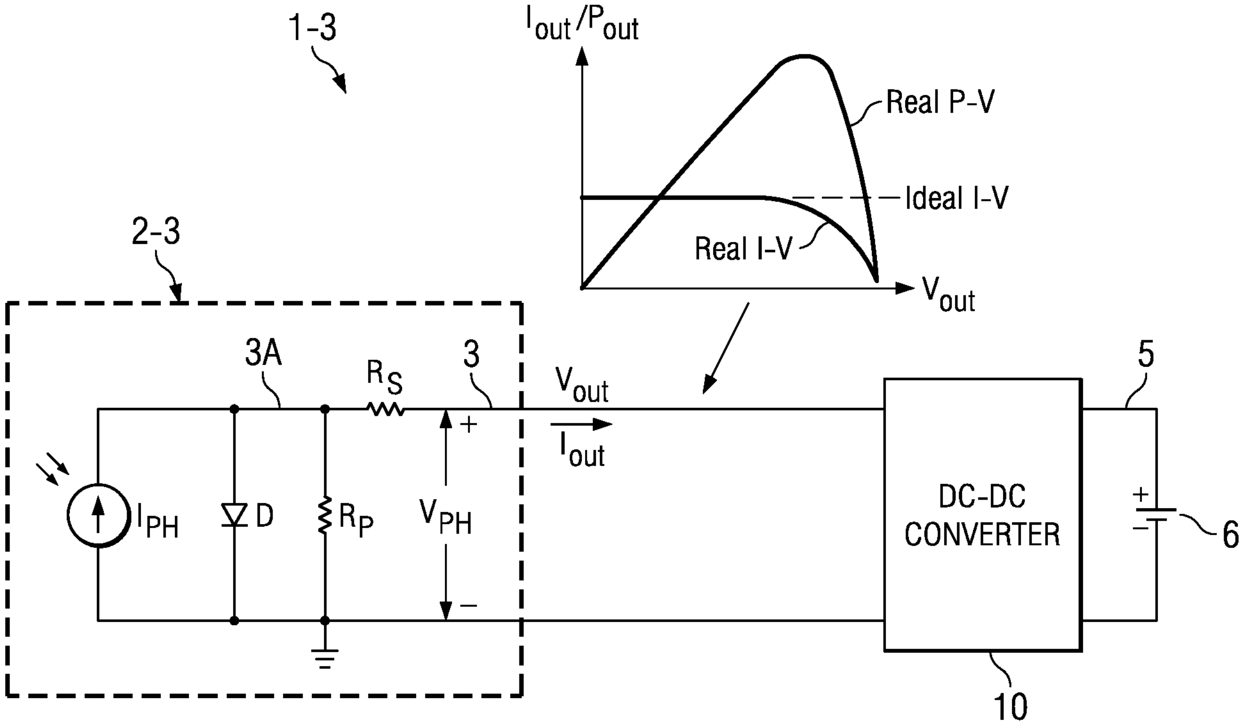


FIG. 3
(PRIOR ART)

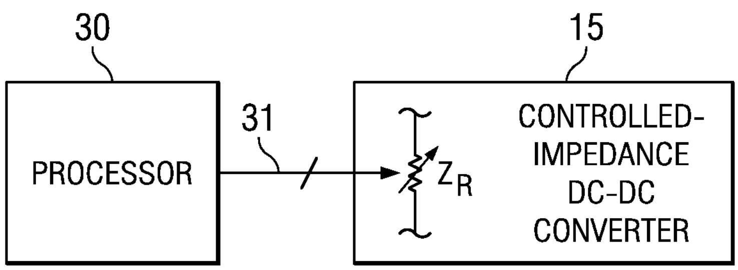
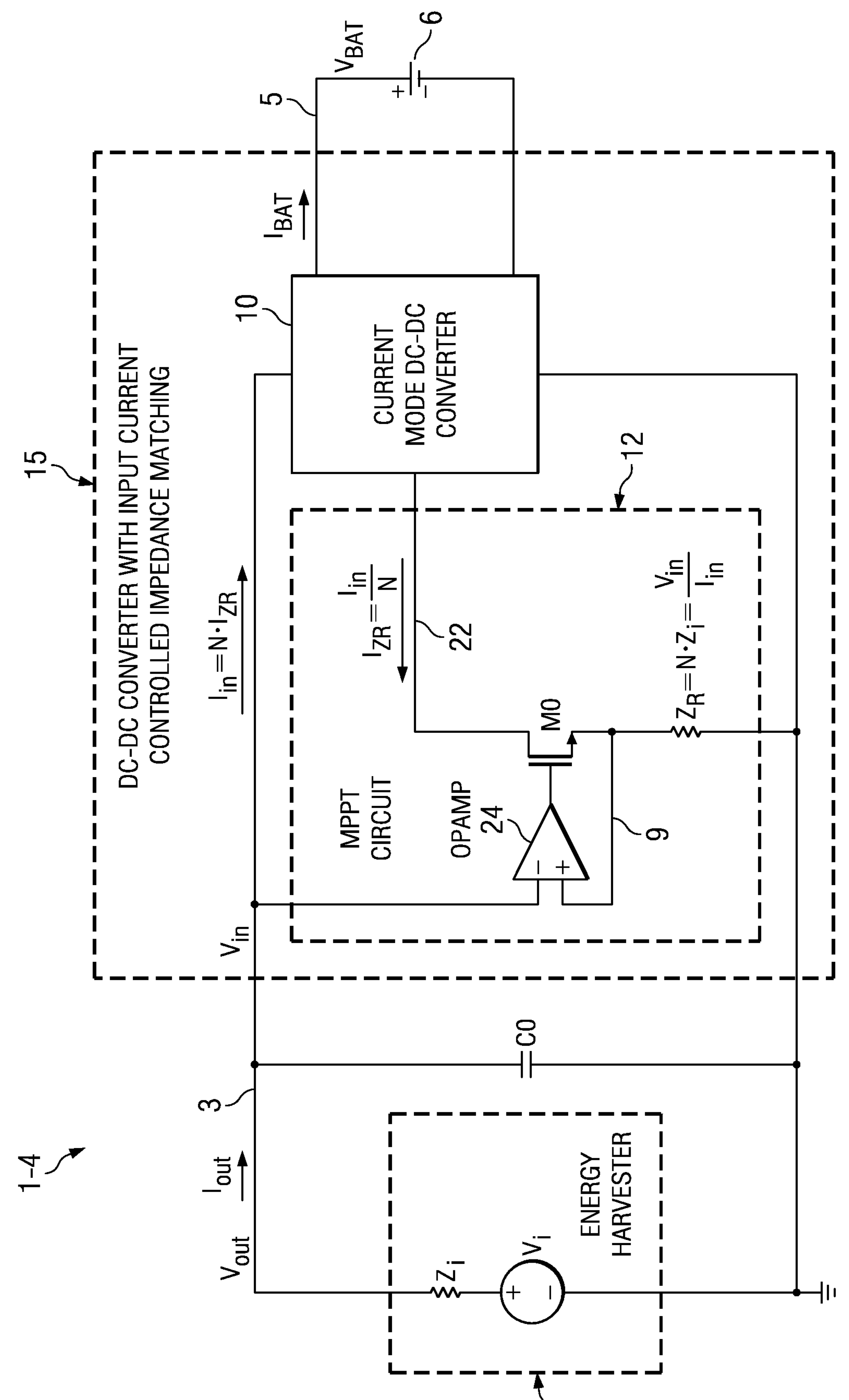


FIG. 6



1–4
15
DC-DC CONVERTER WITH INPUT CURRENT CONTROLLED IMPEDANCE MATCHING
10
CURRENT MODE DC-DC CONVERTER
I_{BAT}
5
V_{BAT}
6
+
−
12
MPPT CIRCUIT
OPAMP
24
−
+
M0
9
22
$I_{ZR} = \frac{I_{in}}{N}$
$Z_R = N \cdot Z_i = \frac{V_{in}}{I_{in}}$
$I_{in} = N \cdot I_{ZR}$
V_{in}
C0
3
V_{out}
I_{out}
Z_i
V_i
+
−
ENERGY HARVESTER
2

FIG. 4

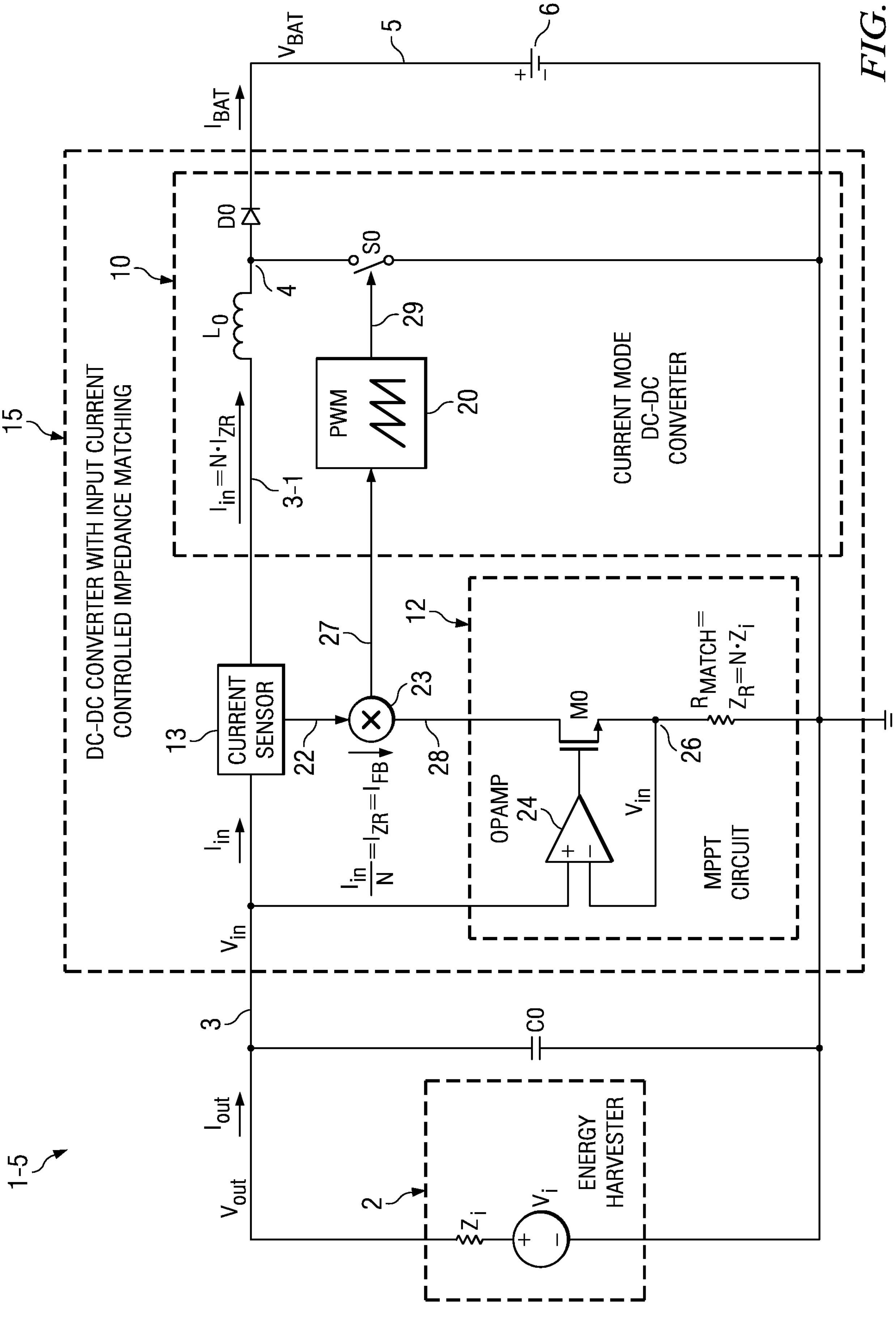

1-5
15
DC-DC CONVERTER WITH INPUT CURRENT CONTROLLED IMPEDANCE MATCHING
10
CURRENT MODE DC-DC CONVERTER
12
MPPT CIRCUIT
OPAMP
24
M0
26
$R_{MATCH}=$
$Z_R=N\cdot Z_i$
13
CURRENT SENSOR
22
23
27
28
$\frac{I_{in}}{N}=I_{ZR}=I_{FB}$
PWM
20
29
S0
D0
L_0
4
$I_{in}=N\cdot I_{ZR}$
3-1
I_{in}
V_{in}
I_{BAT}
V_{BAT}
5
6
3
C0
2
ENERGY HARVESTER
Z_i
V_i
V_{out}
I_{out}

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2010/061532

A. CLASSIFICATION OF SUBJECT MATTER

H02J 7/10(2006.01)i, H02M 3/155(2006.01)i, G05F 1/66(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 7/10; H02J 7/35; H02J 1/10; G05F 1/67; H01L 31/042

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: battery, MPPT, feedback, converter, PWM, photovoltaic

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009-0206666 A1 (SELLA GUY et al.) 20 August 2009 See the abstract; paragraphs [0039], [0070], [0072]; claims 1, 5, 6; figures 3, 6, 7.	1-20
A	"Cascaded H-bridge multilevel converter for grid connected photovoltaic generators with independent maximum power point tracking of each solar array", ALONSO O. et al., IEEE Power Electronics Specialist Conference Proceedings, Vol. 2, pages 731-735, 15 June 2003 See page 731; figure 1.	1-20
A	"Cascaded DC-DC converter connection of photovoltaic modules", WALKER G. R. et al., IEEE Power Electronics Specialists Conference Proceedings, Vol. 1, pages 24-29, 23 June 2002 See page 24; figure 1.	1-20
A	JP 11-103538 A (MY WAY GIKEN KK) 13 April 1999 See the abstract; figures 1-3.	1-20
A	JP 11-041832 A (NIPPON TELEGR & TELEPH CORP <NTT>) 12 February 1999 See the abstract; figures 1, 4.	1-20

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

* Special categories of cited documents:
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"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
16 JUNE 2011 (16.06.2011)	**21 JUNE 2011 (21.06.2011)**

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Facsimile No. 82-42-472-7140

Authorized officer
WEE Jae Woo
Telephone No. 82-42-481-8540

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2010/061532

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2009-0206666 A1	20.08.2009	None	
JP 11-103538 A	13.04.1999	None	
JP 11-041832 A	12.02.1999	None	