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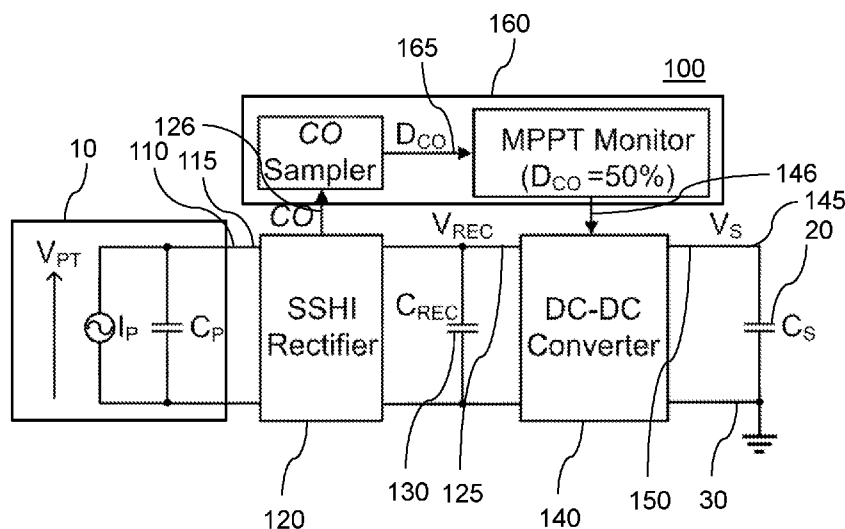
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(54) Title: ENERGY HARVESTER

**Fig. 2(a)**

(57) **Abstract:** An energy harvester comprising: an input port couplable to a vibrating energy source; a rectifier arranged for rectifying the energy from the input port providing rectified energy, and for providing a cut-off signal based on the rectified energy, wherein the cut-off signal has a duty cycle; a rectified energy capacitor receiving the rectified energy; an energy drain arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on a control value; an output port for providing the drained energy to a load; and a power controller generating the control value, and comprising: a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; and a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; wherein the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and wherein the control value is based on the polarity signal and the switch-off control value.

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ENERGY HARVESTER

FIELD OF THE INVENTION

The invention relates to an energy harvester. The invention further relates to an IC comprising the energy harvester. The invention also relates to a method for energy harvesting, an effective energy harvesting controller, method for controlling energy harvesting, and a computer-readable storage medium.

BACKGROUND OF THE INVENTION

Energy harvesting is becoming a common energy source for remotely operating electrical apparatuses, such as sensors for Internet of things, where energy harvesting replaces batteries. Typically, these electrical apparatuses have no or difficult access to mains power. An advantage of energy harvesting is the smaller volume and reduced maintenance costs.

One of the energy sources for energy harvesting is the kinetic energy, which can be converted to electrical energy, typically an AC energy, by a piezoelectric transducer (PT). As the output energy from the PT is AC energy, some rectifiers, typically bias-flip rectifiers, are required for the energy conversion. However, the output power extracted by such rectifiers strongly depends on the impedance matching between the PT and the circuit coupled to the PT.

To maximize the output power, two conventional maximum power point tracking (MPPT) algorithms are often used. The Perturb & Observe (P&O) (a.k.a. hill-climbing) algorithm was proposed which adjusts the rectified output power in a stepwise manner towards the maximum power point (MPP), thus establishing robust and continuous MPPT. However, accurately sensing the rectified output power often requires complex and power-hungry hardware. Another simpler algorithm is based on the fractional open-circuit voltage (FOCV) and involves periodically measuring the PT's open-circuit voltage amplitude (VOC) and regulating the rectified voltage (VREC) to a voltage level (VMPP), which corresponds to the MPP. However, the PT must be periodically disconnected from the rectifier to measure VOC, resulting in wasted energy, while the inherent delay in sensing VOC variations reduces the overall tracking efficiency. Furthermore, a calibration step is usually necessary to determine VMPP, since this depends on the actual PT voltage flip efficiency (η_F) of the bias-flip rectifier.

To summarize: by using P&O, accurately sensing the rectified output power often requires complex and power-hungry hardware; by using FOCV, the PT must be periodically disconnected from the rectifier to measure VOC, resulting in source energy wastage, while the inherent delay in sensing VOC variations reduces the overall tracking efficiency. Further, FOCV also requires flip efficiency (η_F) calibration.

SUMMARY OF THE INVENTION

An object of the invention is to overcome one or more of the disadvantages mentioned above.

According to a first aspect of the invention, an energy harvester comprising: an input port couplable to a vibrating energy source; a rectifier arranged for rectifying the energy from the input port providing rectified energy, and for providing a cut-off signal based on the rectified energy, wherein the cut-off signal has a duty cycle; a rectified energy capacitor receiving the rectified energy; an energy drain

arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on a control value; an output port for providing the drained energy to a load; and a power controller generating the control value, and comprising: a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; and a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; wherein the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and wherein the control value is based on the polarity signal and the switch-off control value.

The energy harvester is arranged for harvesting electrical energy from a vibrating energy source couplable to an input port of the energy harvester. The energy harvester is typically an electrical circuit. The energy harvester comprises a rectifier, a rectified energy capacitor, an energy drain, an output port and a power controller.

The rectifier is arranged for rectifying the energy from the input port. The input port provides AC energy. The rectifier is further arranged for providing a cut-off signal. The cut-off signal has a duty cycle. The cut-off signal and/or the duty cycle (DCO) of the cut-off signal may be affected by the rectifying time. The DCO and/or cut-off signal is typically related to the mode of the rectifier, such as if the rectifier is conducting or not. The DCO and/or cut-off signal may relate to the voltage across the rectified energy capacitor and the open circuit voltage of the vibrating energy source. The periodicity of the cut-off signal is typically based on the periodicity of the vibrating source.

The rectified energy capacitor receives the rectified energy from the rectifier. One side of the rectified energy capacitor is typically coupled to a common ground from the energy harvester. The other side of the rectified energy capacitor is typically directly coupled to the rectifier. The voltage across the rectified energy capacitor is labelled rectified voltage VREC. The increase of the VREC typically depends on the flipping efficiency of the rectifier. The cut-off signal may also be affected by the flipping efficiency.

The energy drain is arranged for draining the rectified energy. The drained energy is drained from the rectified energy capacitor. The rectified energy capacitor stores the rectified energy. The rectified energy stored in the rectified energy capacitor relates to a voltage, which is the rectified voltage VREC, over the rectified energy capacitor, according to:

$$V_{rec} = \frac{E_{rec}}{Q_{rec}}$$

wherein EREC is the rectified energy and QREC is the charge of the rectified energy capacitor. The drained energy is provided by the energy drain. The amount of energy drained is based on a control value.

The output port is arranged for providing the drained energy to a load. The load may be a processor and/or a sensor of an Internet-of-things apparatus. The load may have a larger capacitance used as storage of drained energy for further use or conversion, such as a DC-DC converter for providing the appropriate voltage or voltages to e.g. a microprocessor or a sensor.

The power controller is arranged for controlling the control value based on the duty cycle of the cut-off signal. It is an insight of the inventor that the maximum power point tracking (MPPT) efficiency for the current energy harvester relates to the duty cycle of the cut-off signal and/or DCO. Depending on

the shape of the signal provided to the input port by the vibrating energy source, although the relation may change, there is a relation between to the duty cycle of the cut-off signal and/or DCO. Examples of signal shapes are sinus, square, triangle, sawtooth, pulsed, decaying, etc. Examples of pulsed signals are monopolar, symmetric bipolar, asymmetric bipolar, or balanced asymmetric bipolar. As an example, the maximum power point tracking (MPPT) efficiency for the current energy harvester for a sinusoidal signal provided to the input port adheres to the following relation:

$$\eta_{MPPT} = 1 - \cos^2(\pi D_{CO})$$

wherein DCO is the duty cycle of the cut-off signal, and η_{MPPT} is the ratio of the actual rectified power to the optimal output power at the MPP. Thus, $\eta_{MPPT} = 1$ indicates the maximum power that can be obtained by regulating DCO at 50%.

η_{MPPT} is independent of the VOC and η_F . This provides the advantage that the MPPT can be optimized, or even achieved, without the need for calibration of the energy harvester apart of or together with the vibrating energy source. The absence of the need for calibration greatly simplifies production and use under different conditions. Also, inefficiency or need for recalibration over time due to aging of the vibrating energy source and/or the energy harvester is obviated.

The vibrating energy source is continuously coupled to the energy harvester, more precise via the input port to the rectifier without uncoupling the vibrating energy source. As the vibrating energy source is continuously coupled to the rectifier, the energy harvester has no separate power tracking cycles or modes. Due to the continuous coupling no energy from the vibrating energy source is lost or wasted, or in other words the energy harvesting from the vibrating energy source is optimized.

Furthermore, as the vibrating energy source is continuously coupled to the energy harvester, the power tracking can be done continuously, preventing any delays in power tracking. Due to the absence of separate power tracking cycles or modes, changes of the energy provided by the vibrating energy source are instantly tracked by the current energy harvester without delay.

The power controller comprises a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold, preferably 50% duty cycle; and the control value is based on the polarity signal. The polarity signal provides a simple control signal indicating the duty cycle being below or above the duty cycle threshold. The duty cycle threshold may be set depending on the type and/or shape of the signal from the vibrating energy source. As an example, a duty cycle of 50% is optimal for a sinusoidal signal coming from the vibrating energy source.

The power controller comprises a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and the control value is based on the switch-off control value. This embodiment uses a lower rectified energy value as threshold to switch off the energy drain to let rectified energy build up in the rectified capacitor for advantageously preventing energy loss in the rectifier and/or DC-DC converter. Furthermore, this embodiment provides the advantage of optimizing η_{MPPT} typically in situations of ramp-up, change, or temporal dip or spike of the energy generated by the PT.

According to another aspect of the invention, an IC comprising an energy harvester according to any of the mentioned embodiments or claims, wherein the IC comprises ports for coupling to an externally arranged inductor of the SSHI rectifier; and/or wherein the IC comprises ports for coupling to an externally arranged inductor of the DC-DC converter. According to another embodiment an external inductor is shared between the SSHI rectifier and the DC-DC converter. In this embodiment, the IC typically comprises a port for connecting to the shared inductor. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention.

According to another aspect of the invention, an energy harvesting power source, comprising: a vibrating energy source; and an energy harvester according to any of the mentioned embodiments or claims. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention.

According to another aspect of the invention, a method for energy harvesting comprising the steps of: receiving vibrating energy from a kinetic energy source; rectifying the received energy providing rectified energy and a cut-off signal based on the rectified energy, wherein the cut-off signal has a duty cycle; providing the rectified energy to a rectified energy capacitor; converting the rectified energy to DC energy, wherein the amount of energy converted is based on a control value; providing the DC energy to a load; generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; setting a lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below the lower rectified energy value; generating the control value based on the polarity signal and the switch-off control value. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention.

According to another aspect of the invention, an energy harvesting controller comprising: a receiver arranged for receiving a cut-off signal having a duty cycle, wherein the cut-off signal is based on rectified energy, which is provided to a rectified energy capacitor, and which is based on rectified vibrating energy originating from a kinetic energy source; a controller generating a control value, and comprising: a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; and a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; wherein the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and wherein the control value is based on the polarity signal and the switch-off control value; and a transmitter arranged for providing the control value to an energy drain arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on the control value. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention.

According to another aspect of the invention, a method for controlling energy harvesting comprising the steps of: receiving a cut-off signal having a duty cycle, wherein the cut-off signal is based on rectified energy, which is provided to a rectified energy capacitor, and which is based on rectified

vibrating energy originating from a kinetic energy source; generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; setting a lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below the lower rectified energy value; generating a control value based on the polarity signal and the switch-off control value; and providing the control value to an energy drain arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on a control value. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention. In an embodiment of the method for controlling energy harvesting, the step of generating the control value comprises the step of changing the control value such that the duty cycle of the cut-off signal is regulated towards substantially 50%, preferably approaches substantially 50%. The range of the duty cycle is selected such that the advantage of optimizing power transfer and even sub-optimal power transfer but still improved over the prior art is obtained while maintaining simplicity of the solution.

According to another aspect of the invention, a computer-readable storage medium comprising instructions which, when executed by a computer, cause the computer to carry out the steps of any of the mentioned embodiments or claims for the method for controlling energy harvesting. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention.

According to another aspect of the invention, an energy harvester comprising: an input port couplable to a vibrating energy source; a rectifier arranged for rectifying the energy from the input port providing rectified energy, and for providing a cut-off signal based on the rectified energy, wherein the cut-off signal has a duty cycle; a rectified energy capacitor receiving the rectified energy; an energy drain arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on a control value; an output port for providing the drained energy to a load ; and a power controller generating the control value, and comprising: a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; wherein the duty cycle sampler comprises: a high capacitor circuit arranged for measuring a time the cut-off signal is high; a low capacitor circuit arranged for measuring a time the cut-off signal is low; and a polarity comparator arranged for generating a polarity signal based on comparing the high capacitor circuit measurement and the low capacitor circuit measurement; and an energy drain controller generating the control value based on the polarity signal. This aspect of the invention provides the same advantageous as mentioned for the other aspects of the invention. The duty cycle sampler advantageously comprises separate circuits for measuring the time when the cut-off signal is respectively high and low. This separate measurement allows for a relatively simple comparison of two values provided by these two circuits. In a further embodiment of the energy harvester, the high capacitor circuit uses a high capacitor for the measurement of the high capacitor circuit; and/or the low capacitor circuit uses a low capacitor for the measurement of the low capacitor circuit. Typically, both circuits use capacitors for the measurement. This aspect of the invention may specifically be combined with embodiments detailing the high capacitor circuit and/or the low capacitor circuit.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

In an embodiment of the energy harvester, the range set-up block is arranged for setting the switch-off control value at a percentage of the rectified energy in the rectified energy capacitor; and the power controller generates the control value based on comparing the rectified energy in the rectified energy capacitor and the lower rectified energy value such that the rectified energy in the rectified energy capacitor is drained if the rectified energy in the rectified energy capacitor is above the lower rectified energy value. The percentage of the rectified energy in the rectified energy capacitor is typically a percentage of the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold. The percentage advantageously allows to control the ripple of the rectified energy in the rectified energy capacitor. In a further embodiment of the energy harvester, the percentage is settable in a range of 90% to 100%, preferably 95% to 99.9%, more preferably 96% to 99.8%, most preferably 97% to 99.5%. The settable percentage may be implemented with the use of changing a capacitance as shown in part of Figure 5(a) shown with a light grey background. The example in Figure 5(a) may vary the capacitance with 44 fF, 75 fF and 150 fF.

In an embodiment of the energy harvester, the duty cycle sampler comprises: a high capacitor circuit arranged for measuring a time the cut-off signal is high; a low capacitor circuit arranged for measuring a time the cut-off signal is low; and a polarity comparator arranged for generating the polarity signal based on comparing the high capacitor circuit measurement and the low capacitor circuit measurement. The duty cycle sampler advantageously comprises separate circuits for measuring the time when the cut-off signal is respectively high and low. This separate measurement allows for a relatively simple comparison of two values provided by these two circuits. In a further embodiment of the energy harvester, the high capacitor circuit uses a high capacitor for the measurement of the high capacitor circuit; and/or the low capacitor circuit uses a low capacitor for the measurement of the low capacitor circuit. Typically, both circuits use capacitors for the measurement.

In a further embodiment of the energy harvester, the high capacitor circuit loads the high capacitor for the measurement of the high capacitor circuit; and/or the low capacitor circuit loads the low capacitor for the measurement of the low capacitor circuit. The loading over time of a capacitor may advantageously be used as a time indication. Typically, both circuits use the loading of the capacitors for the measurement.

In a further embodiment of the energy harvester, the high capacitor has a settable capacitance; and/or wherein the low capacitor has a settable capacitance. This embodiment advantageously allows to adapt the duty cycle sampler to different frequencies or periods of the cut-off signal. Further, this embodiment advantageously allows to adapt the duty cycle sampler to set different values for the duty cycle threshold. Typically, both circuits have a settable capacitance.

In a further embodiment of the energy harvester, the cut-off signal has a cut-off frequency; the polarity comparator has a tipping point indicative of a duty cycle; the power controller comprises a settings register for setting the capacitance of the high capacitor and/or the capacitance of the low capacitor; and the capacitance of the high capacitor and the capacitance of the low capacitor are settable for changing the tipping point and/or for adapting to a range of cut-off frequencies. This embodiment advantageously allows to adapt the duty cycle sampler to different frequencies or periods of the cut-off

signal via the settings register. Further, this embodiment advantageously allows to adapt the duty cycle sampler to set different values for the duty cycle threshold via the settings register. Typically, the settings register is adapted to set the capacitance of both capacitors.

In a further embodiment of the energy harvester, the power controller comprises a reset circuit resetting the high capacitor circuit and the low capacitor circuit such that the high capacitor circuit and the low capacitor circuit measure respectively the high time and low time per period of the cut-off signal. The reset circuit allows to measures changes in the duty cycle per period. This embodiment is therefore advantageously quickly adapting to changes in the duty cycle. This embodiment therefore advantageously allows to accurately control the ripple in the duty cycle and therefore the optimal power point tracking, such as reducing the ripple in duty cycle tracking and therefore optimizes the power point tracking. Furthermore, the quickly adapting to changes in the duty cycle also allows this embodiment to accurately track changes in the vibrating energy source for optimizing the power drawn from the vibrating energy source while the behaviour of the vibrating energy source is changing. The measurement per period of the cut-off signal thus advantageously provides an agile energy harvester.

In an embodiment of the energy harvester, the power controller is arranged for changing the control value such that the duty cycle of the cut-off signal is regulated towards substantially 50%, preferably approaches substantially 50%. Changing the control value such that the duty cycle of the cut-off signal is regulated towards substantially 50% causes the formula for the η_{MPPT} for a sinusoidal signal to evaluate to the value 1. A value of 1 for the η_{MPPT} means that the power transfer is maximized or in other words the energy harvested from the vibrating energy source is maximized. Furthermore, the change of the ratio η_{MPPT} for a sinusoidal signal is expressed as follows:

$$\eta'_{MPPT} = \pi \sin(2\pi D_{CO})$$

For a duty cycle of substantially 50%, this expression evaluates to 0, indicating a slow change of η_{MPPT} from 1, thus variations in the duty cycle near 50% result in a small change of η_{MPPT} . Thus, optimizing energy harvesting is advantageously robust for changes or detection errors in the duty cycle. For example, a DCO error of $\pm 5\%$ (or $\pm 10\%$) results in η_{MPPT} still greater than 97% (or 90%). In a further embodiment of the energy harvester, the duty cycle of the cut-off signal is in the range of 30% to 70%, preferably 40% to 60%, more preferably 45% to 55%, most preferably substantially 50%. The range of the duty cycle is selected such that the advantage of optimizing power transfer and even sub-optimal power transfer but still improved over the prior art is obtained while maintaining simplicity of the solution.

In an embodiment of the energy harvester, the rectifier comprises a rectification bridge, which is a rudimentary first step in converting AC energy to DC energy. In a further embodiment, the rectification bridge is a full rectification bridge advantageously using the positive and the negative part of the AC energy or voltage cycle.

In an embodiment of the energy harvester, the rectifier has a conductive mode indicative of the rectifier conducting energy, and a cut-off mode indicative of the rectifier not conducting energy; the rectifier comprises a mode detection block providing the cut-off signal; and the cut-off signal is indicative of the mode of the rectifier. The rectifier is typically in conductive mode when a voltage is across the rectifier causing a current to flow through the rectifier. When the rectifier conducts energy, such as a current, the vibrating energy source, typically in series with the rectifier via the input port, is also conducting energy, such as a current. Thus, the cut-off signal is thus indirectly an indicator if the vibrating energy

source is conducting energy. The energy harvester may therefore indirectly regulate the duty cycle of the vibrating energy source. Regulating the duty cycle of the vibrating energy source provides the advantage of providing the option to maximize the energy transfer or energy obtained from the vibrating energy source.

5 In a further embodiment of the energy harvester, the mode detection block comprises an active diode and/or an active rectifier arranged for detecting the mode of the rectifier. The active diode may be sampled to detect if energy flows through the active diode. The active diode is typically in series with the rectifier. If the active diode is conducting, the rectifier is conducting and is thus in the conductive mode. The active diode typically comprises an active element such as a MOSFET, power MOSFET and/or
10 bipolar junction transistor acting as switch. The control gate of the active element is used to actively switch the active element in conductive mode. The control gate is controlled by the energy and/or voltage difference across the active element. Sampling the control gate signal therefore advantageously provides if the rectifier is in conductive mode or cut-off mode. Thus, sampling or tapping the control gate signal advantageously provides a cut-off signal. In a further embodiment of the energy harvester, the active
15 diode is arranged downstream of the rectification bridge. This provides the advantage that the energy and/or voltage is already rectified simplifying the circuitry of the active diode.

In an embodiment of the energy harvester, the rectifier is an SSHI rectifier. The SSHI rectifier advantageously optimizes the energy and/or power transfer from the vibrating energy source.

In an embodiment of the energy harvester, the energy drain is a DC-DC converter converting
20 the rectified energy to DC energy. The DC-DC converter advantageously combines further stabilizing the rectified energy for use as DC energy and acting as a controllable energy drain typically by switching the DC-DC converter on and off. In a further embodiment of the energy harvester, the DC-DC converter is a boost converter or a buck converter, preferably a buck-boost converter, comprising at least one switch; and the at least one switch is controlled based on the control value. The at least one switch
25 advantageously provides a simple control mechanism for controlling the amount of drained energy.

In an embodiment of the energy harvester, the energy harvester is arranged for coupling to a Piezo electric element. The Piezo electric element may be a vibrating energy source picking up vibrations from the surroundings.

In an embodiment of the energy harvester, the power controller comprises a duty cycle
30 sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold, preferably 50% duty cycle; and the control value is based on the polarity signal. The polarity signal provides a simple control signal indicating the duty cycle being below or above the duty cycle threshold. The duty cycle threshold may be set depending on the type and/or shape of the signal from the vibrating energy source. As an example, a
35 duty cycle of 50% is optimal for a sinusoidal signal coming from the vibrating energy source.

In a further embodiment of the energy harvester, the power controller comprises a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor
40 when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and the control value is based on the switch-off control value. This embodiment uses a lower rectified energy value as

threshold to switch off the energy drain to let rectified energy build up in the rectified capacitor for advantageously preventing energy loss in the rectifier and/or DC-DC converter. Furthermore, this embodiment provides the advantage of optimizing η MPPT typically in situations of ramp-up, change, or temporal dip or spike of the energy generated by the PT.

5 In an embodiment of the energy harvester, the energy drain comprises an on-off switch switching the energy drain on or off; and the control value controls the on-off switch. This advantageously provides a simple implementation.

BRIEF DESCRIPTION OF THE DRAWINGS

10 The invention will be apparent from and elucidated further with reference to the embodiments described by way of example in the following description and with reference to the accompanying drawings, in which:

Figure 1(a) shows the relation of rectified voltage versus power combined with a flow chart for a hill climbing algorithm according to the prior art;

15 Figure 1(b) shows an implementation of the hill climbing algorithm according to the prior art;

Figure 2(a) schematically shows a simplified topology of the energy harvester;

Figure 2(b) schematically shows the cut off signal generation of the energy harvester;

Figure 2(c) schematically shows the relation of duty cycle versus MPPT efficiency;

20 Figure 3 schematically shows a flow chart diagram of MPPT and DC-DC conversion process;

Figure 4 schematically shows the system architecture of the energy harvester;

Figure 5(a) schematically shows of the MPPT control block of the energy harvester with some signals;

25 Figure 5(b) schematically shows the duty cycle sampling method of the energy harvester with some signals;

Figure 6(a) schematically shows measured waveforms of the energy harvester;

Figure 6(b) schematically shows measured waveforms of the energy harvester;

30 Figure 6(c) schematically shows the measured relation of rectified output power versus power;

Figure 7(a) schematically shows the measured relation of duty cycle versus output power;

Figure 7(b) schematically shows the measured relation of rectified voltage versus output power;

35 Figure 7(c) schematically shows the measured relation of open circuit voltage versus MPPT efficiency;

Figure 7(d) schematically shows the measured relation of flipping efficiency versus MPPT efficiency;

Figure 8 shows a comparison table;

40 Figure 9 shows an image of the die of the energy harvester; and

Figure 10 schematically shows an embodiment of a computer program product, computer readable medium and/or non-transitory computer readable storage medium according to the invention.

The figures are purely diagrammatic and not drawn to scale. In the figures, elements which correspond to elements already described may have the same reference numerals.

LIST OF REFERENCE NUMERALS

10, PT	vibrating energy source
20, CS	load
30	ground
100	energy harvester
110	input port
115, VPT	energy from the input port
120	rectifier
125, VREC	rectified energy
126, CO	cut-off signal
130, CREC	rectified energy capacitor
140	energy drain
145, VS	drained energy
146	control value
150	output port
160	power controller, MPPT controller
165, DCO	duty cycle cut-off signal

DETAILED DESCRIPTION OF THE FIGURES

The following figures may detail different embodiments. Embodiments can be combined to reach an enhanced or improved technical effect. These combined embodiments may be mentioned explicitly throughout the text, may be hint upon in the text or may be implicit.

Synchronized bias-flip rectifiers, such as synchronized switch harvesting on inductor (SSHI) rectifiers, may be used for piezoelectric energy harvesting (PEH), which can replace the use of batteries in many Internet-of-Things (IoT) applications, thus reducing both system volume and maintenance cost. However, the output power extracted by such rectifiers strongly depends on the impedance matching between the piezoelectric transducer (PT) and the circuit. To maximize this, two maximum power point

tracking (MPPT) algorithms are often used. As shown in Figure 1(a) and Figure 1(b), the Perturb & Observe (P&O) (a.k.a. hill-climbing) algorithm adjusts the rectified output power in a stepwise manner towards the maximum power point (MPP), thus establishing robust and continuous MPPT. However, accurately sensing the rectified output power often requires complex and power-hungry hardware.

Another simpler algorithm is based on the fractional open-circuit voltage (FOCV) and involves periodically measuring the PT's open-circuit voltage amplitude (VOC) and regulating the rectified voltage (VREC) to a level (VMPP), which corresponds to the MPP. However, the PT must be periodically disconnected from the rectifier to measure VOC, resulting in wasted energy, while the inherent delay in sensing VOC variations reduces the overall tracking efficiency. Furthermore, a calibration step is usually necessary to determine VMPP, since this depends on the actual PT voltage flip efficiency (η_F) of the bias-flip rectifier.

A duty-cycle-based MPPT algorithm is proposed, which combines the advantages of the P&O and FOCV algorithms while eliminating their drawbacks.

Figure 2(a) schematically shows an implementation of the energy harvester 100. The energy harvester comprises an input port 110, a rectifier 120, a rectified energy capacitor 130, an energy drain 140, an output port 150 and a power controller 160. Figure 2(a) further shows a vibrating energy source 10, a load 20 and a ground 30. The vibrating energy source is coupled to the input power for receiving energy 115, such as a voltage, from the vibrating energy source. The vibrating energy source may be a PT modelled as an AC current source generating a current I_p parallel to a capacitor C_p .

The rectifier may be a SSHI rectifier. The rectifier provides rectified energy 125 to the rectified energy capacitor. The rectified energy may be a rectified voltage. The rectifier further provides a cut-off signal 126 to the power controller.

The energy drain may be a DC-DC converter. The energy drain drains rectified energy from the rectified energy capacitor. The amount of energy drained is based on a control value 146 provided by the power controller. The energy drain converts the rectified energy to drained energy 145 provided to the output port. The output port is coupled to the load for providing the drained energy to the load.

Figure 2(b) schematically shows several signals of the energy harvester. The top signal I_p is the AC current from the vibrating energy source, such as the current from a PT. The middle signal is a voltage signal present over the vibrating energy source and resulting from the PT and the energy harvester, typically the behaviour of the energy harvester. The bottom signal is the cut-off signal provided by the rectifier. Figure 2(c) schematically shows the relation of duty cycle versus MPPT efficiency or η_{MPPT} .

Figure 2(a), when the vibrating energy source, such as a PT, is vibrating at resonant frequency with a weakly coupled coefficient, it may be modelled by an AC current source I_p in parallel with a capacitor C_p . The corresponding system may comprise of an SSHI rectifier, a buck-boost DC-DC converter to adjust the VREC, and an MPPT controller. While extracting the AC energy from the PT, the rectifier will periodically switch between conducting and cut-off modes. It can generate a cut-off signal, CO, which is "high" when the rectifier is cut-off and "low" when it is conducting (bottom waveform Figure 2(b)). The proposed MPPT algorithm exploits the relationship between the MPPT efficiency (η_{MPPT}) and the duty-cycle of CO (DCO). Through mathematical analysis, the inventors have found that $\eta_{MPPT} = 1 - \cos^2(\pi DCO)$, where η_{MPPT} is the ratio of the actual rectified power to the optimal output power at the MPP for sinusoidal signals at the input port. In Figure 2(a), operation at the MPP for a sinusoidal input

signal can then be achieved by regulating DCO to 50%, regardless of VOC and η_F . Furthermore, due to the squared cosine relationship, the algorithm is robust to DCO sensing errors. For example, a DCO error of $\pm 5\%$ (or $\pm 10\%$) results in η_{MPPT} still greater than 97% (or 90%). Compared to the conventional P&O and FOCV algorithms, the proposed duty-cycle-based MPPT algorithm has the following advantages: 1) it is independent of VOC or η_F , so no calibration is required; 2) the PT is always connected to the rectifier, so no energy is wasted; and 3) continuous MPPT is possible. These advantages and its robustness to DCO errors simplify its circuit implementation, resulting in a prototype PEH system dissipating only 307nW in the MPPT controller or power controller.

The flowchart of the proposed MPPT algorithm is shown in Figure 3. The DCO, may be sampled in every CO period (every half vibration cycle) by measuring its ON and OFF pulse widths. If $DCO < 50\%$, energy harvested by the PT will charge the rectifier output capacitor CREC, thus increasing its voltage VREC towards the MPP. If DCO exceeds 50%, this means that VREC exceeds the VMPP, so some of the energy in CREC is transferred to the load, such as storage capacitor CS, via an energy drain, such as a DC-DC buck-boost converter, in order to maintain VREC around VMPP by regulating DCO to around 50%. At the beginning of the DC-DC transfer, a voltage level VRECS, which is slightly lower than the initial VREC, is set as the lower threshold of the VREC hysteresis window. Clocked by an on-chip oscillator (OSC), the energy drain conversion, such as the buck-boost conversion, operates for multiple cycles until $VREC < VRECS$. This flow will repeat until next time when DCO exceeds 50%, to achieve MPPT.

The proposed architecture may comprise an SSHI rectifier with its own control block, and a buck-boost converter with an MPPT controller (Figure 4). The SSHI rectifier may comprise a FBR, an active diode and an off-chip inductor LM shared with the DC-DC converter. When the voltage across the PT (VPT) needs to be flipped, the FBR switches from conducting mode to cut-off mode. This causes a CO rising edge, which is used to generate an SSHI flipping pulse that briefly connects LM across the PT, thus initiating a closed RLC loop to flip VPT. The CO signal is also sent to the MPPT controller, where its duty-cycle DCO is measured. If DCO exceeds 50%, the DC-DC converter is enabled at the next low-CO period to transfer some energy from CREC to CS, and thus maintaining VREC around the VMPP. A hysteresis window, with a lower threshold VRECS (a fraction of the initial VREC), prevents VREC from dropping too much. The upper hysteresis threshold is automatically set to VMPP by the $DCO = 50\%$ condition, and so an explicit voltage threshold is not required. The buck-boost converter is controlled by an on-chip OSC, and uses the shared LM to transfer energy from CREC to CS. The timing of the switching signal, SPD, is controlled by a zero-crossing detector (ZCD).

Figures 5(a) and 5(b) show a possible implementation of the power controller or MPPT controller. The DCO is sensed by two equal on-chip capacitors, CRGL and CRGR. When CO is high, CRGL is charged by an on-chip current source to V_H ; while CRGR is charged to V_L when CO is low. The CRGL typically is the high capacitor. The CRGR typically is the low capacitor. To cope with a wide range of PT vibration frequency (half of CO frequency), CRGL and CRGR can be adjusted in 8 steps between 5.4pF and 32.2pF, as shown with the grey background in Figure 5(b). The resulting voltages V_H and V_L are compared to generate the polarity signal or PO signal, which indicates the polarity of DCO around the 50% target. When $DCO > 50\%$, PO stays low; otherwise, a pulse is generated. The CRGL and CRGR are reset by a short pulse, SCV, at the end of each CO period. When PO stays low, meaning that DCO

exceeds 50% (or VREC exceeds VMPP), a DC-DC enable signal, COM, is generated to start the DC-DC conversion. The lower hysteresis threshold, VRECS, is generated by a switched-capacitor voltage divider. In this design, VRECS can be turned from $97\% \times VREC$ to $99.5\% \times VREC$ to adjust the ripple of VREC during DC-DC conversion. VRECS may be the switch-off control value. Alternatively, VRECS may be the lower rectified energy value. The percentage may be used to enable the different capacitors shown with the light grey background in Figure 5(a). VREC and VRECS are provided to a comparator, which may be named enable comparator. The enable comparator may generate the control value 146. The enable comparator may be arranged to provide a status to the control value for enabling the energy drain only when VREC is higher than VRECS, such that for example during startup the energy drain will not be enabled.

The proposed circuit was fabricated in a 180-nm BCD process and has an active area of 0.47mm^2 (Figure 9). It was tested with a commercial PT (PEH-S128-H5FR-1107YB) excited at its resonance frequency of 230 Hz. Figures 6(a), 6(b) and 6(c) show the measured waveforms. The system starts from the cold state with $VOC=1.5\text{V}$ and $LM=27\mu\text{H}$. VREC then increases steadily because DCO is less than 50% and the DC-DC converter is disabled. When VREC reaches VMPP1 ($\sim 2.47\text{V}$), DCO is 50%, indicating that the MPP has been reached. The DC-DC converter is then enabled by the MPPT controller to maintain VREC at 2.47V by transferring the harvested energy to VS during the MPPT1 period. When the vibration excitation is increased to $VOC = 2\text{V}$, the new VMPP increases and DCO becomes lower than 50%. As a result, the MPPT block disables the DC-DC converter so that VREC builds up. After DCO reaches 50% again, VREC is maintained at the new MPP ($\sim 3.42\text{V}$) in the MPPT2 period. The MPPT convergence time is highly dependent on the capacitance of CREC and acceleration variation. The bottom-right plot shows the measured output power versus VREC with the same VOC and LM as used in the waveform. It shows that the optimal VMPP for 1.5-V VOC (or 2-V VOC) is 2.4V (or 3.3V), which is very close to the regulated VREC of 2.47V (or 3.42V) measured and shown in the waveform. During each stable MPPT period when $VS > VREC$, VREC shows a slightly positive slope. This is because the gate-driving voltage for the bias-flip switches uses the higher of VS and VREC for better SSHI performance. The gradually increasing VS reduces the ON resistance in the RLC loop, which increases the flip efficiency η_F , resulting in a slightly increasing VMPP. Nevertheless, the proposed MPPT algorithm can still adaptively regulate VREC to the varying VMPP since it is independent of VOC and η_F . The zoomed-in VREC waveform is also shown in the figure. Each regulation process is done through a number of DC-DC conversion cycles indicated by the pulse signal SPC.

The output power of an SSHI rectifier versus the DCO with 1.5-V and 2-V VOC is shown in Figure 7(a). At their peak power points, the optimal duty cycles are 47.58% and 48.52%, respectively, which are close to 50%. These results validate the analytical expression of η_{MPPT} . The shift of optimal DCO from 50% to a slightly lower value is mainly due to the non-zero voltage drop of the active rectifier. However, thanks to the high tolerance to DCO errors of the proposed MPPT algorithm, even when the system regulates DCO to 50% instead of to the actual optimal value, the MPPT efficiency η_{MPPT} is maintained above 99%. In figure 7(b), the measured output power from an FBR and the proposed SSHI rectifier with different inductors (different η_F) at $VOC=2\text{V}$ shows that the proposed rectifier achieves a peak output power of $272.5\mu\text{W}$, with 738% enhancement compared to an FBR ($36.9\mu\text{W}$). The MPPT efficiency with different input VOC and η_F is also shown in Figures 7(c) and 7(d). From these two plots, it

can be seen that, regardless of VOC and η_F , the optimal DCO is always around 50%, while the η_{MPPT} remains high. The peak η_{MPPT} is 98% and the average efficiency is around 96% for a wide range of VOC and η_F .

Figure 8 compares the proposed duty-cycle based MPPT algorithm with the state-of-the-art. It occupies a compact area, while enabling continuous MPPT without using an explicit power sensor. It shows no dependency on rectifier parameters: VOC and η_F . It achieves 98% peak MPPT efficiency and up to 738% power extraction enhancement compared to an FBR.

Figure 9 schematically shows an embodiment of a computer program product 1000, computer readable medium 1010 and/or non-transitory computer readable storage medium according to the invention comprising computer readable code 1020.

It will also be clear that the above description and drawings are included to illustrate some embodiments of the invention, and not to limit the scope of protection. These embodiments are within the scope of protection and the essence of this invention and are obvious combinations of prior art techniques and the disclosure of this patent. Devices functionally forming separate devices may be integrated in a single physical device.

The term "substantially" herein, such as in "substantially all emission" or in "substantially consists", will be understood by the person skilled in the art. The term "substantially" may also include embodiments with "entirely", "completely", "all", etc. Hence, in embodiments the adjective substantially may also be removed. Where applicable, the term "substantially" may also relate to 90% or higher, such as 95% or higher, especially 99% or higher, even more especially 99.5% or higher, including 100%. The term "comprise" also includes embodiments wherein the term "comprises" means "consists of".

The term "functionally" will be understood by, and be clear to, a person skilled in the art. The term "substantially" as well as "functionally" may also include embodiments with "entirely", "completely", "all", etc. Hence, in embodiments the adjective functionally may also be removed. When used, for instance in "functionally parallel", a skilled person will understand that the adjective "functionally" includes the term substantially as explained above. Functionally in particular is to be understood to include a configuration of features that allows these features to function as if the adjective "functionally" was not present. The term "functionally" is intended to cover variations in the feature to which it refers, and which variations are such that in the functional use of the feature, possibly in combination with other features it relates to in the invention, that combination of features is able to operate or function. For instance, if an antenna is functionally coupled or functionally connected to a communication device, received electromagnetic signals that are received by the antenna can be used by the communication device. The word "functionally" as for instance used in "functionally parallel" is used to cover exactly parallel, but also the embodiments that are covered by the word "substantially" explained above. For instance, "functionally parallel" relates to embodiments that in operation function as if the parts are for instance parallel. This covers embodiments for which it is clear to a skilled person that it operates within its intended field of use as if it were parallel.

Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in

other sequences than described or illustrated herein. Thus, these terms are not necessarily intended to indicate temporal or other prioritization of such elements.

The devices or apparatus herein are amongst others described during operation. As will be clear to the person skilled in the art, the invention is not limited to methods of operation or devices in operation.

It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments without departing from the scope of the appended claims. In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. Use of the verb "to comprise" and "to include", and its conjugations does not exclude the presence of elements or steps other than those stated in a claim. Also, the use of introductory phrases such as "at least one" and "one or more" in the claims should not be construed to imply that the introduction of another claim element by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim element to inventions containing only one such element, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an." The article "a" or "an" preceding an element does not exclude the presence of a plurality of such elements.

The invention may be implemented by means of hardware comprising several distinct elements, and by means of a suitably programmed computer. In the device or apparatus claims enumerating several means, several of these means may be embodied by one and the same item of hardware.

The invention further applies to an apparatus or device comprising one or more of the characterising features described in the description and/or shown in the attached drawings. The invention further pertains to a method or process comprising one or more of the characterising features described in the description and/or shown in the attached drawings.

It will be appreciated that the invention also applies to computer programs, particularly computer programs on or in a carrier, adapted to put the invention into practice. The program may be in the form of a source code, a code intermediate source and an object code such as in a partially compiled form, or in any other form suitable for use in the implementation of the method according to the invention. It will also be appreciated that such a program may have many different architectural designs. For example, a program code implementing the functionality of the method or system according to the invention may be sub-divided into one or more sub-routines. Many different ways of distributing the functionality among these sub-routines will be apparent to the skilled person. The sub-routines may be stored together in one executable file to form a self-contained program. Such an executable file may comprise computer-executable instructions, for example, processor instructions and/or interpreter instructions (e.g. Java interpreter instructions). Alternatively, one or more or all of the sub-routines may be stored in at least one external library file and linked with a main program either statically or dynamically, e.g. at run-time. The main program contains at least one call to at least one of the sub-routines. The sub-routines may also comprise function calls to each other. An embodiment relating to a computer program product comprises computer-executable instructions corresponding to each processing stage of at least one of the methods set forth herein. These instructions may be sub-divided into sub-routines and/or stored in one or more files that may be linked statically or dynamically. Another embodiment relating to a

computer program product comprises computer-executable instructions corresponding to each means of at least one of the systems and/or products set forth herein. These instructions may be sub-divided into sub-routines and/or stored in one or more files that may be linked statically or dynamically.

5 The carrier of a computer program may be any entity or device capable of carrying the program. For example, the carrier may include a data storage, such as a ROM, for example, a CD ROM or a semiconductor ROM, or a magnetic recording medium, for example, a hard disk. Furthermore, the carrier may be a transmissible carrier such as an electric or optical signal, which may be conveyed via electric or optical cable or by radio or other means. When the program is embodied in such a signal, the carrier may be constituted by such a cable or other device or means. Alternatively, the carrier may be an
10 integrated circuit in which the program is embedded, the integrated circuit being adapted to perform, or used in the performance of, the relevant method.

The various aspects discussed in this patent can be combined in order to provide additional advantages.

CLAIMS

1. Energy harvester (100) comprising:

- an input port (110) couplable to a vibrating energy source (10);
- a rectifier (120) arranged for rectifying the energy (115) from the input port providing rectified energy (125), and for providing a cut-off signal (126) based on the rectified energy, wherein the cut-off signal has a duty cycle (165);

- a rectified energy capacitor (130) receiving the rectified energy;
- an energy drain (140) arranged for draining the rectified energy and providing drained energy (145), wherein the amount of energy drained is based on a control value (146);

- an output port (150) for providing the drained energy to a load (20); and
- a power controller (160) generating the control value, and comprising:

- a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; and

- a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; wherein the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and

wherein the control value is based on the polarity signal and the switch-off control value.

2. Energy harvester according to the preceding claim,

wherein the range set-up block is arranged for setting the switch-off control value at a percentage of the rectified energy in the rectified energy capacitor; and

wherein the power controller generates the control value based on comparing the rectified energy in the rectified energy capacitor and the lower rectified energy value such that the rectified energy in the rectified energy capacitor is drained if the rectified energy in the rectified energy capacitor is above the lower rectified energy value.

3. Energy harvester according to the preceding claim, wherein the percentage is settable in a range of 90% to 100%, preferably 95% to 99.9%, more preferably 96% to 99.8%, most preferably 97% to 99.5%.

4. Energy harvester according to any of the preceding claims, wherein the duty cycle sampler comprises:

- a high capacitor circuit arranged for measuring a time the cut-off signal is high;
- a low capacitor circuit arranged for measuring a time the cut-off signal is low; and
- a polarity comparator arranged for generating the polarity signal based on comparing the high capacitor circuit measurement and the low capacitor circuit measurement.

5. Energy harvester according to the preceding claim,
wherein the high capacitor circuit uses a high capacitor for the measurement of the high capacitor circuit; and/or

5 wherein the low capacitor circuit uses a low capacitor for the measurement of the low capacitor circuit.

6. Energy harvester according to the preceding claim,
wherein the high capacitor circuit loads the high capacitor for the measurement of the high capacitor circuit; and/or

10 wherein the low capacitor circuit loads the low capacitor for the measurement of the low capacitor circuit.

7. Energy harvester according to any of the preceding claims 5-6,
wherein the high capacitor has a settable capacitance; and/or

15 wherein the low capacitor has a settable capacitance.

8. Energy harvester according to the preceding claim,
wherein the cut-off signal has a cut-off frequency;
wherein the polarity comparator has a tipping point indicative of a duty cycle;

20 wherein the power controller comprises a settings register for setting the capacitance of the high capacitor and/or the capacitance of the low capacitor; and
wherein the capacitance of the high capacitor and the capacitance of the low capacitor are settable for changing the tipping point and/or for adapting to a range of cut-off frequencies.

25 9. Energy harvester according to any of the preceding claims 4-8, wherein the power controller comprises a reset circuit resetting the high capacitor circuit and the low capacitor circuit such that the high capacitor circuit and the low capacitor circuit measure respectively the high time and low time per period of the cut-off signal.

30 10. Energy harvester according to any of the preceding claims, wherein the power controller is arranged for changing the control value such that the duty cycle of the cut-off signal is regulated towards substantially 50%, preferably approaches substantially 50%.

35 11. Energy harvester according to the preceding claim, wherein the duty cycle of the cut-off signal is in the range of 30% to 70%, preferably 40% to 60%, more preferably 45% to 55%, most preferably substantially 50%.

12. Energy harvester according to any of the preceding claims, wherein the rectifier comprises a rectification bridge, preferably a full rectification bridge.

40

13. Energy harvester according to any of the preceding claims,
wherein the rectifier has a conductive mode indicative of the rectifier conducting energy, and a
cut-off mode indicative of the rectifier not conducting energy;
wherein the rectifier comprises a mode detection block providing the cut-off signal; and
5 wherein the cut-off signal is indicative of the mode of the rectifier.
14. Energy harvester according to the preceding claim,
wherein the mode detection block comprises an active diode arranged for detecting the mode of
the rectifier; and
10 wherein when also depending on claim 12, the active diode is arranged downstream of the
rectification bridge.
15. Energy harvester according to any of the preceding claims, wherein the rectifier is an SSHI
rectifier.
15
16. Energy harvester according to any of the preceding claims, wherein the energy drain is a DC-
DC converter converting the rectified energy to DC energy.
17. Energy harvester according to the preceding claim,
20 wherein the DC-DC converter is a boost converter or a buck converter, preferably a buck-boost
converter, comprising at least one switch; and
wherein the at least one switch is controlled based on the control value.
18. Energy harvester according to any of the preceding claims, wherein the energy harvester is
25 arranged for coupling to a Piezo electric element.
19. Energy harvester according to any of the preceding claims,
wherein the energy drain comprises an on-off switch switching the energy drain on or off; and
wherein the control value controls the on-off switch.
30
20. IC comprising an energy harvester according to any of the claims 1-19,
wherein, when depending on claim 15, the IC comprises ports for coupling to an externally
arranged inductor of the SSHI rectifier; and/or
wherein, when depending on claim 17, the IC comprises ports for coupling to an externally
35 arranged inductor of the DC-DC converter.
21. Energy harvesting power source, comprising:
- a vibrating energy source; and
- an energy harvester according to any of the claims 1-19.
40

22. Method for energy harvesting comprising the steps of:

- receiving vibrating energy from a kinetic energy source;
- rectifying the received energy providing rectified energy and a cut-off signal based on the rectified energy, wherein the cut-off signal has a duty cycle;
- providing the rectified energy to a rectified energy capacitor;
- converting the rectified energy to DC energy, wherein the amount of energy converted is based on a control value;
- providing the DC energy to a load;
- generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold;
- setting a lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and
- providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below the lower rectified energy value;
- generating the control value based on the polarity signal and the switch-off control value.

23. Energy harvesting controller comprising:

- a receiver arranged for receiving a cut-off signal having a duty cycle, wherein the cut-off signal is based on rectified energy, which is provided to a rectified energy capacitor, and which is based on rectified vibrating energy originating from a kinetic energy source;
- a controller generating a control value, and comprising:
 - a duty cycle sampler generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold; and
 - a range set-up block providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below a lower rectified energy value; wherein the range set-up block is arranged for setting the lower rectified energy value based on the rectified energy in the rectified energy capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and
 - wherein the control value is based on the polarity signal and the switch-off control value; and
- a transmitter arranged for providing the control value to an energy drain arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on the control value.

24. Method for controlling energy harvesting comprising the steps of:

- receiving a cut-off signal having a duty cycle, wherein the cut-off signal is based on rectified energy, which is provided to a rectified energy capacitor, and which is based on rectified vibrating energy originating from a kinetic energy source;
- generating a polarity signal based on the cut-off signal, wherein the polarity signal indicates if the duty cycle of the cut-off signal is above or below a duty cycle threshold;
- setting a lower rectified energy value based on the rectified energy in the rectified energy

capacitor when the polarity signal flips to indicate a duty cycle of above the duty cycle threshold; and

- providing a switch-off control value for switching off the energy drain if the rectified energy in the rectified energy capacitor sinks below the lower rectified energy value;

- generating a control value based on the polarity signal and the switch-off control value; and

5 - providing the control value to an energy drain arranged for draining the rectified energy and providing drained energy, wherein the amount of energy drained is based on a control value.

25. Method for controlling energy harvesting according to the preceding claim, wherein the step of generating the control value comprises the step of changing the control value such that the duty cycle of
10 the cut-off signal is regulated towards substantially 50%, preferably approaches substantially 50%.

26. Computer-readable storage medium comprising instructions which, when executed by a computer, cause the computer to carry out the steps of any of the claims 24-25.

15

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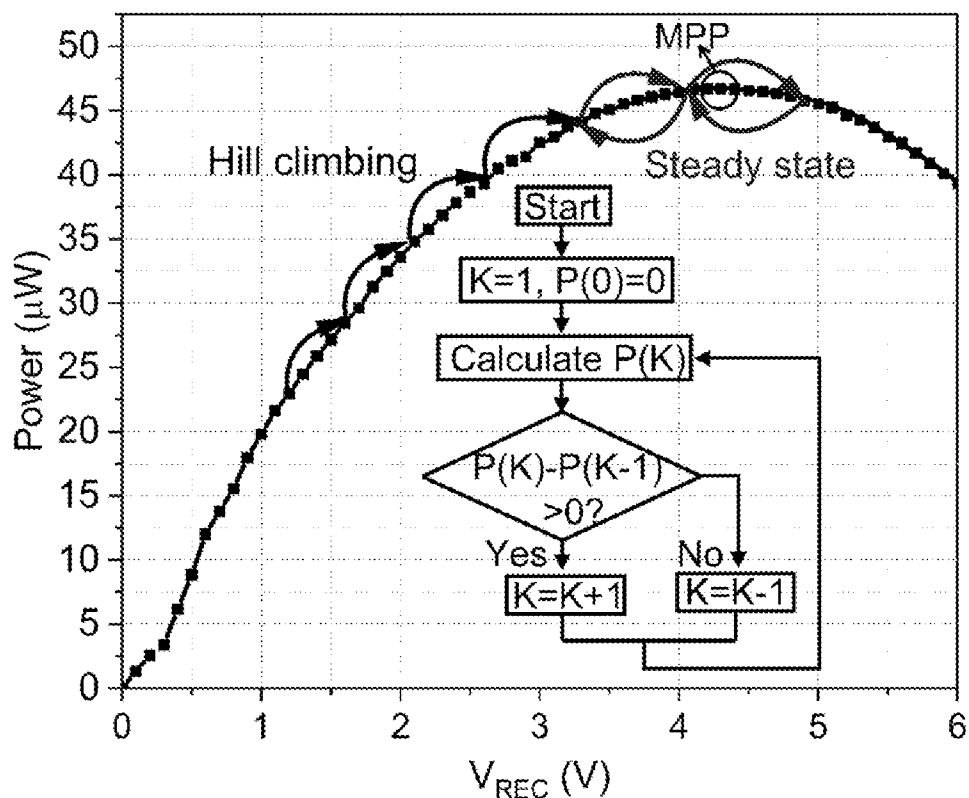


Fig. 1(a) – prior art

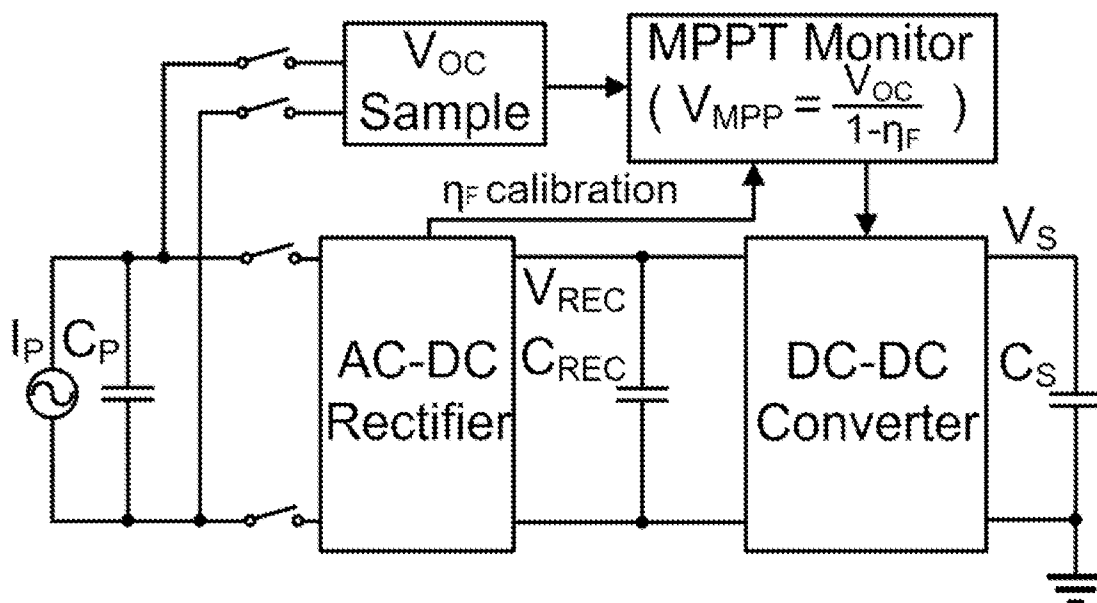


Fig. 1(b) – prior art

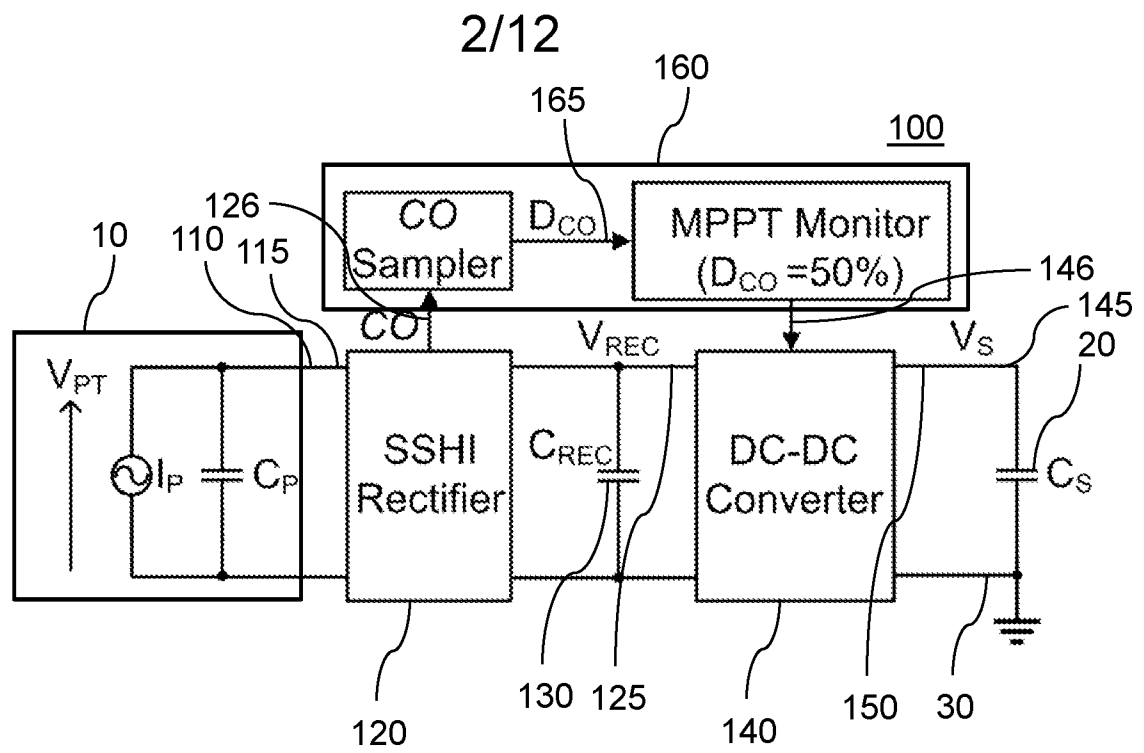


Fig. 2(a)

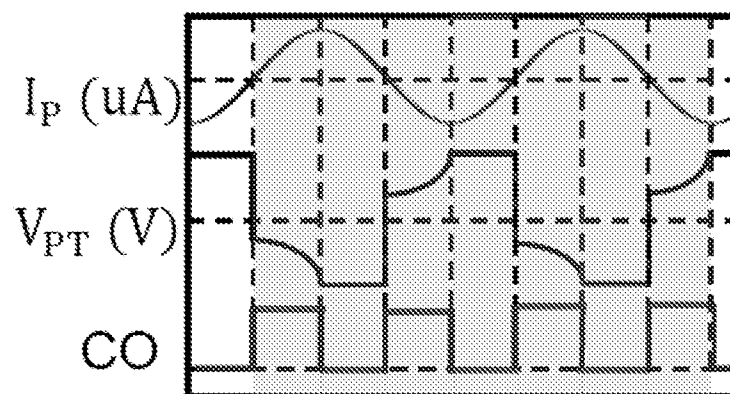


Fig. 2(b)

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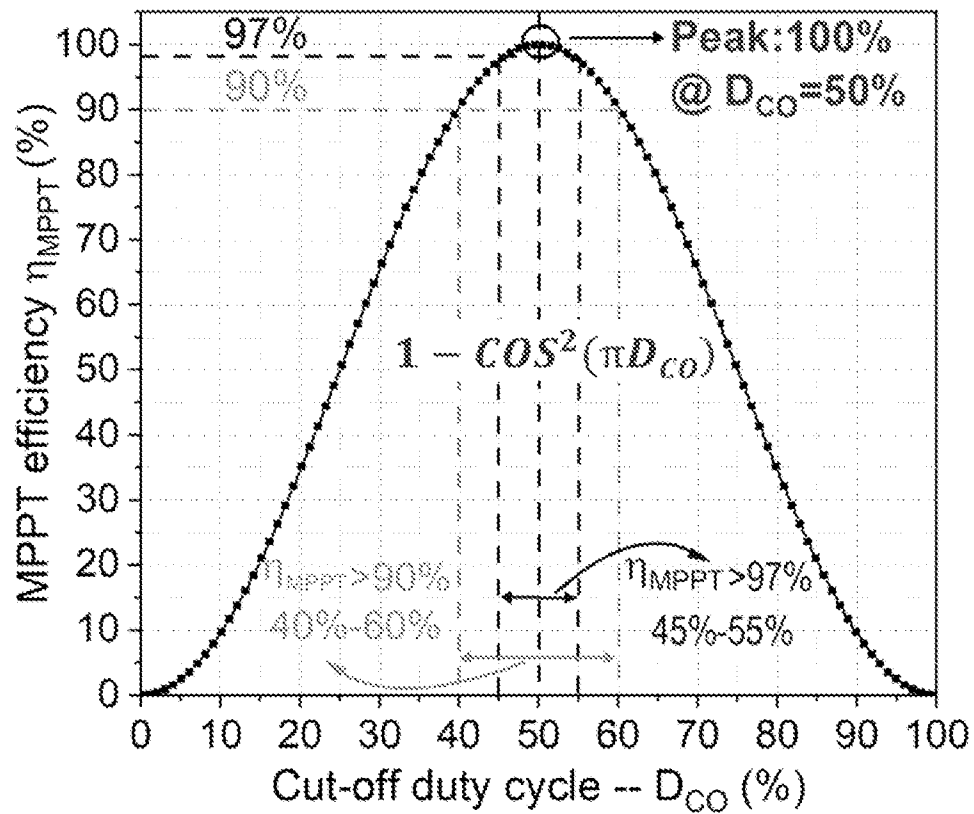


Fig. 2(c)

Duty Cycle Based MPPT Algorithm

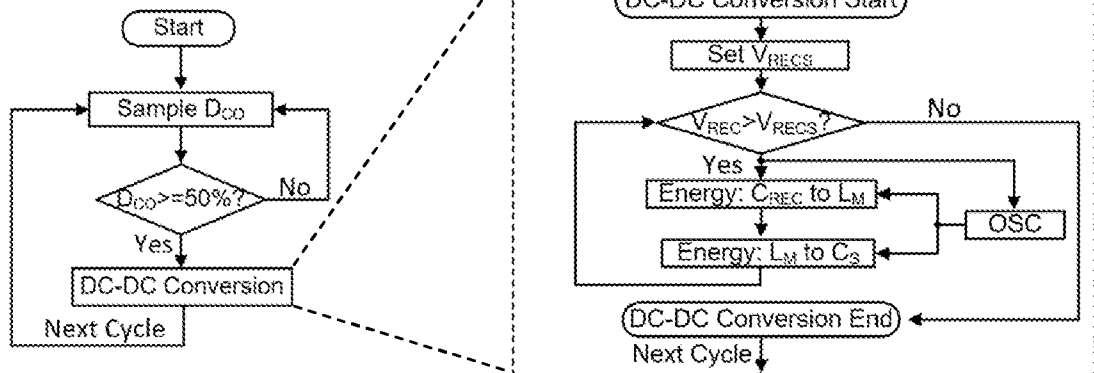


Fig. 3

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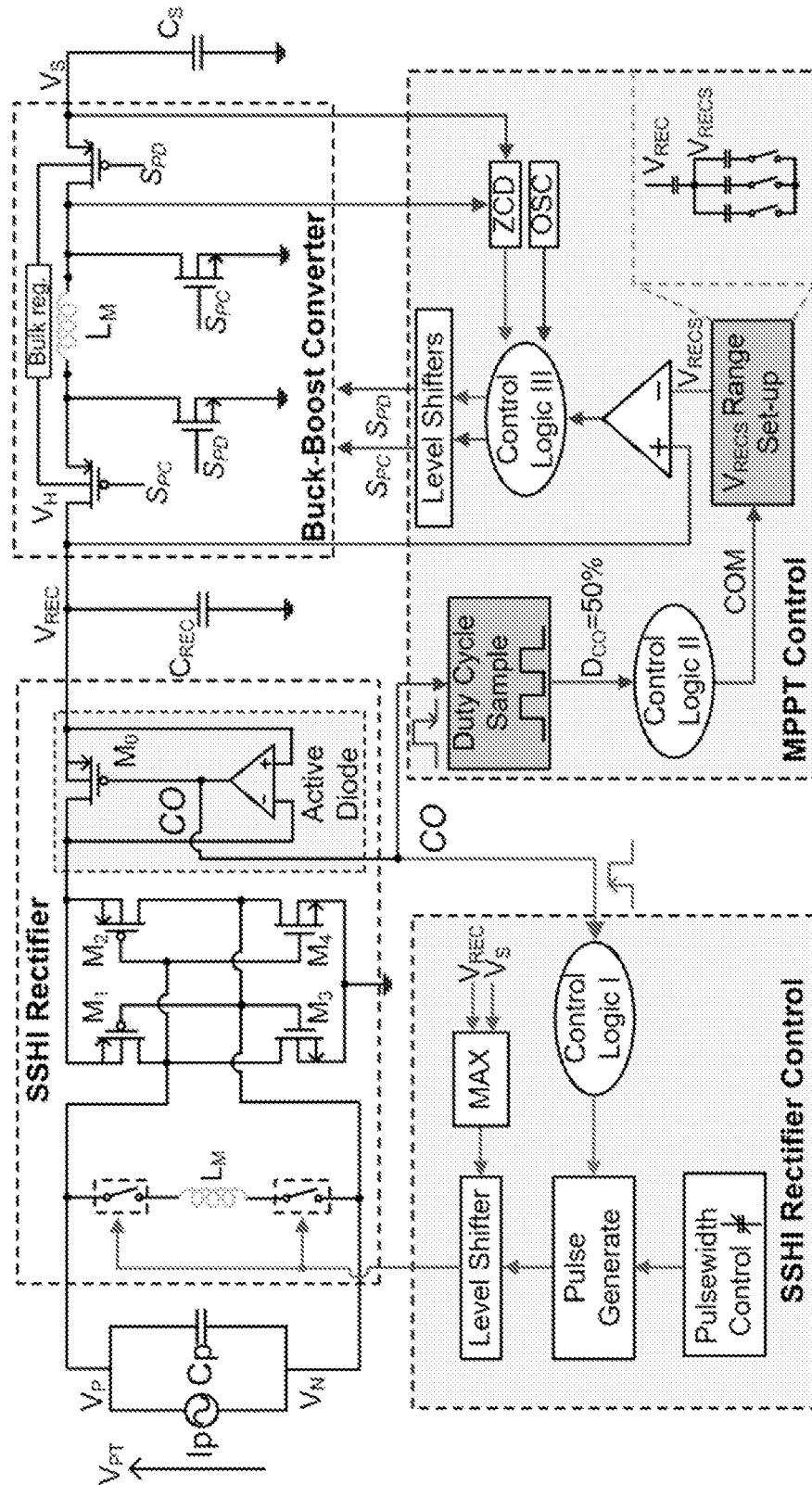


Fig. 4

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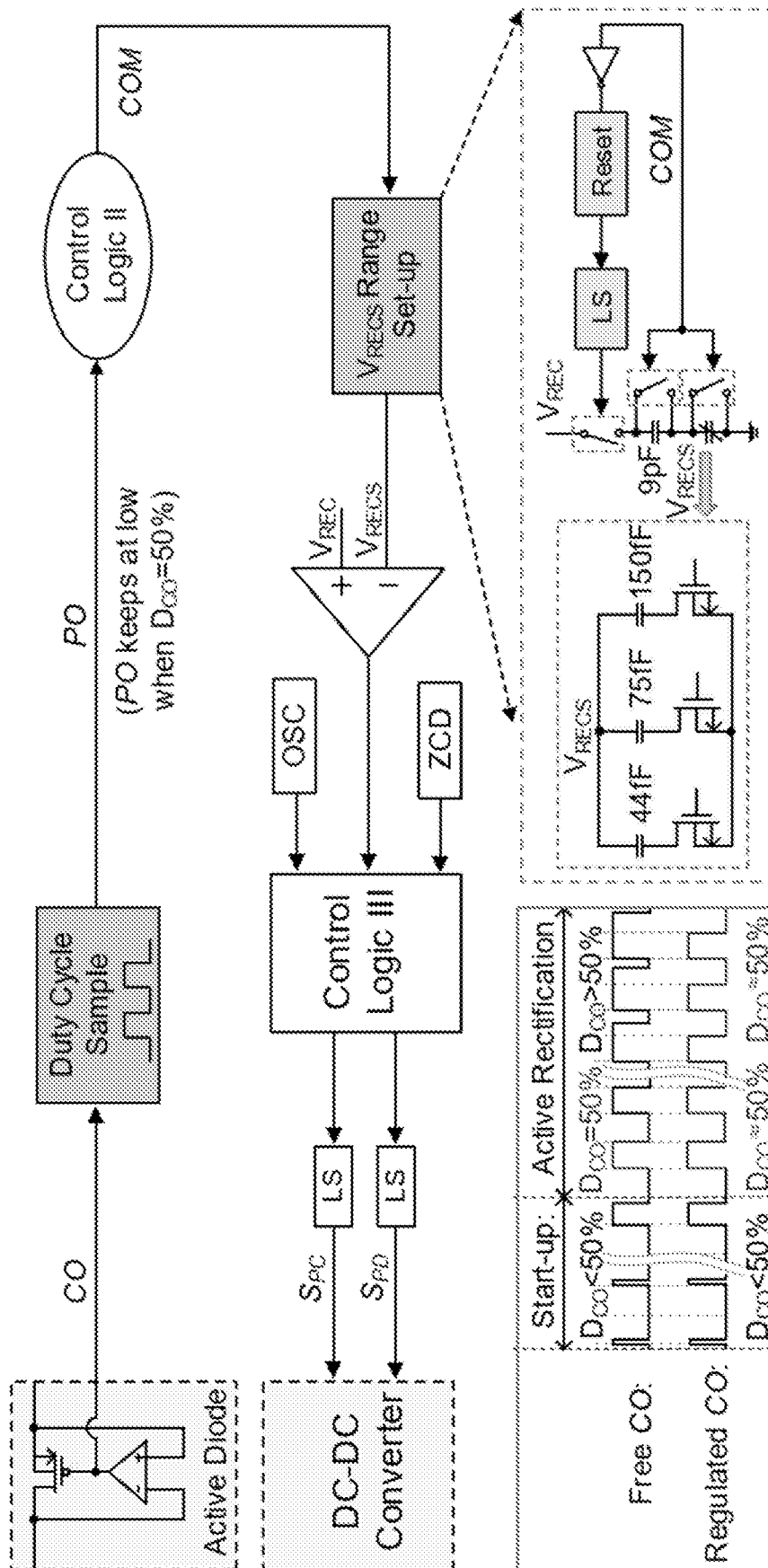


Fig. 5(a)

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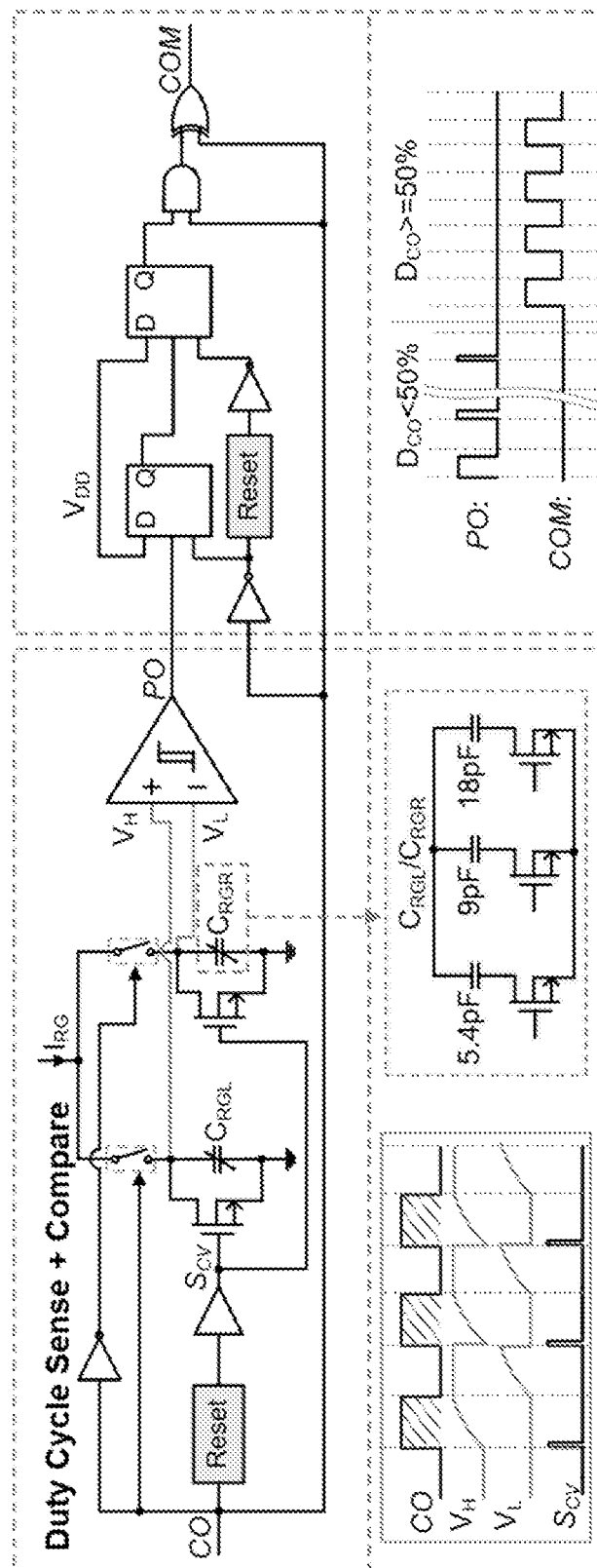


Fig. 5(b)

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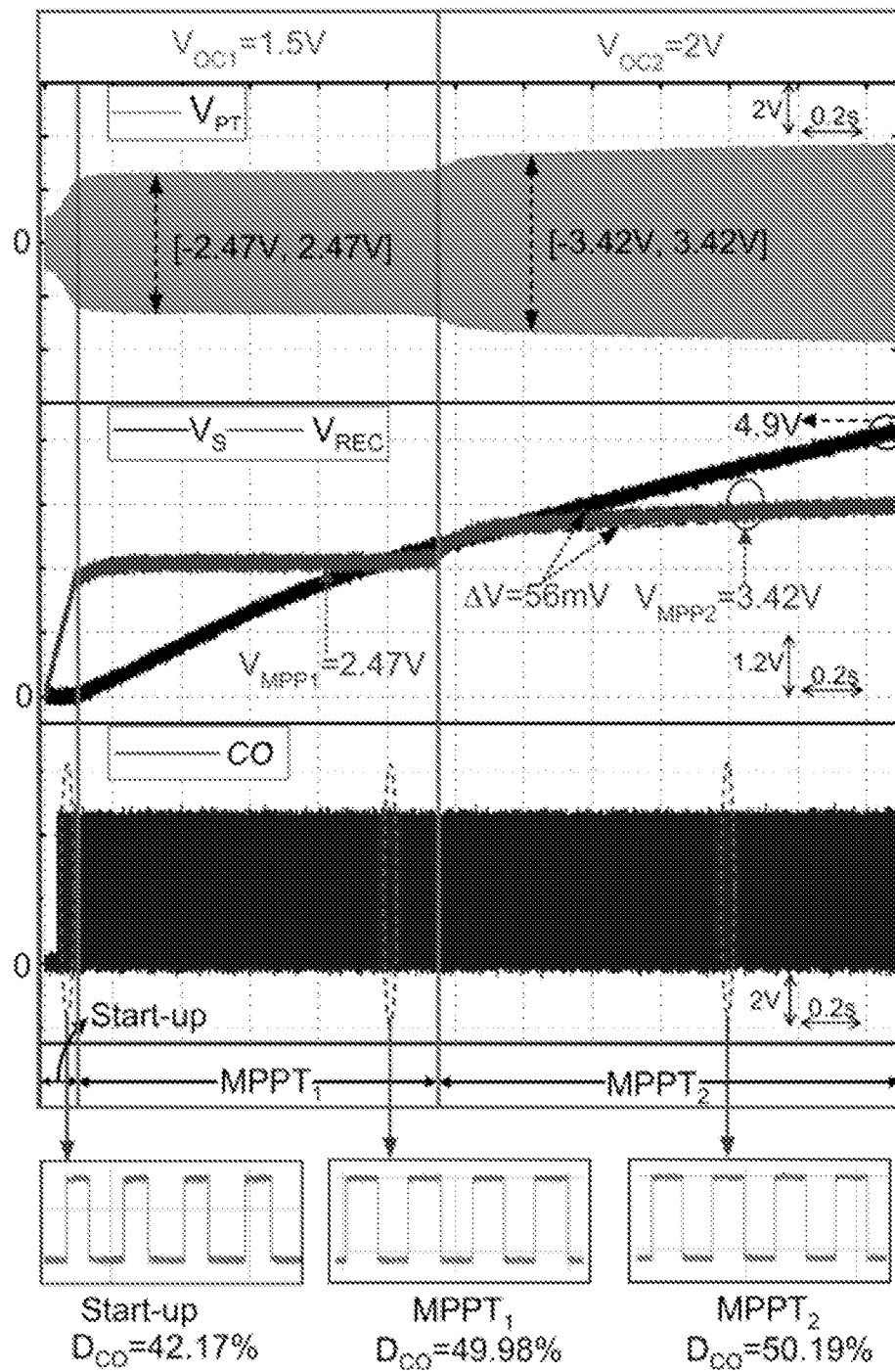


Fig. 6(a)

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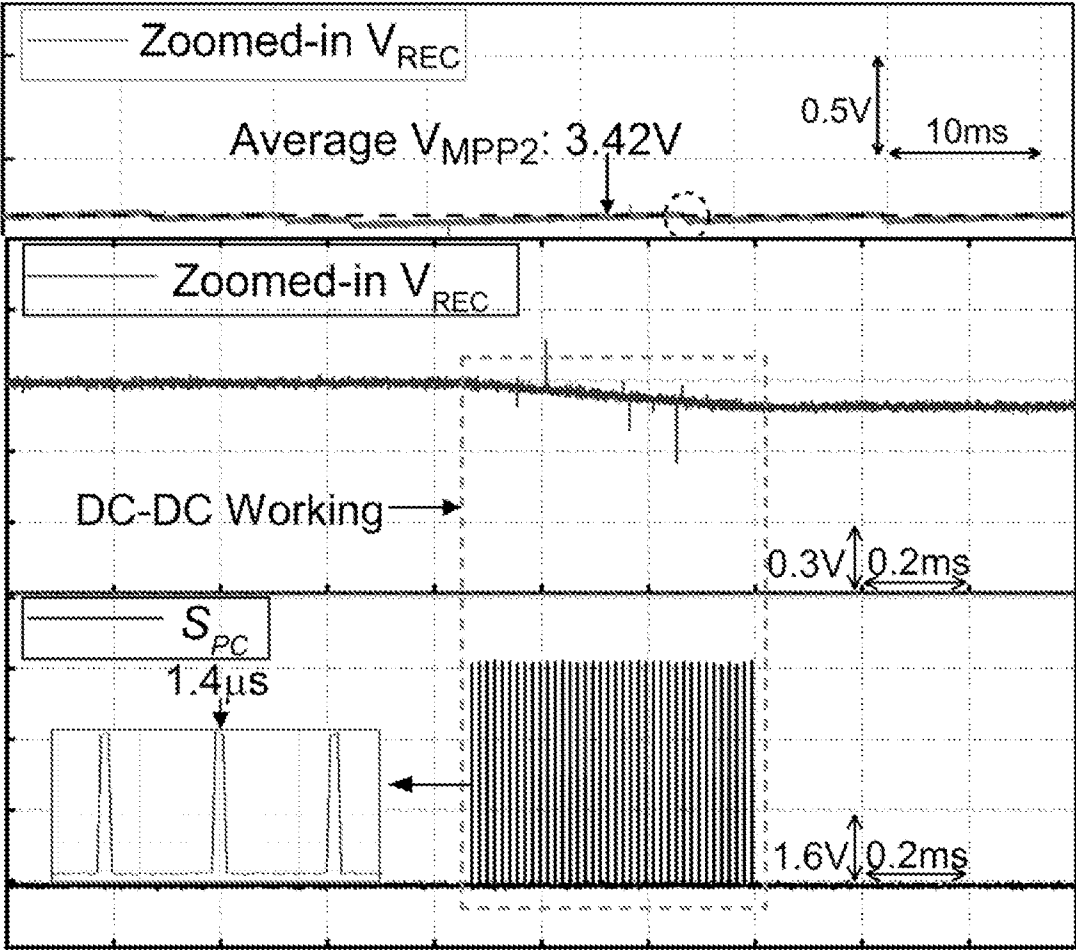


Fig. 6(b)

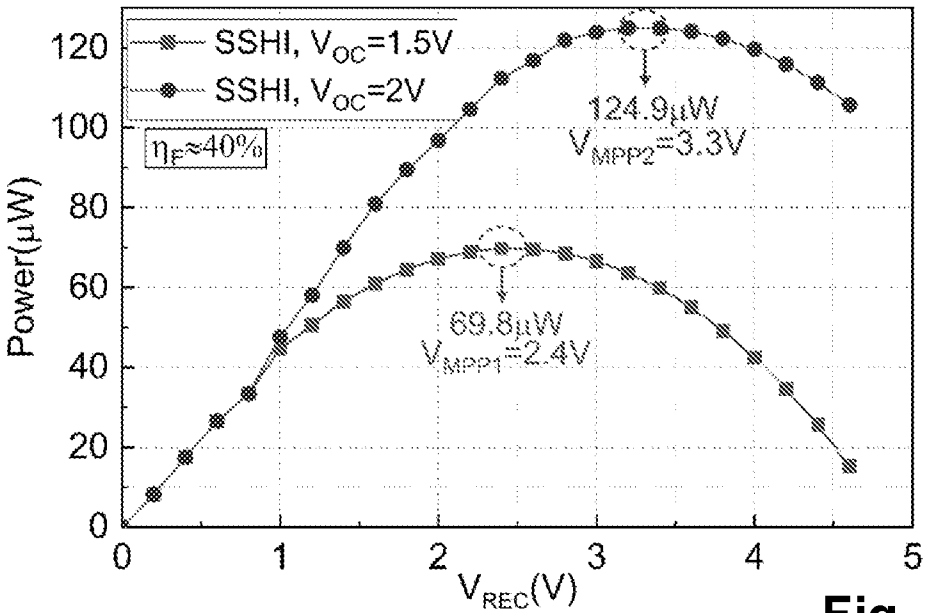


Fig. 6(c)

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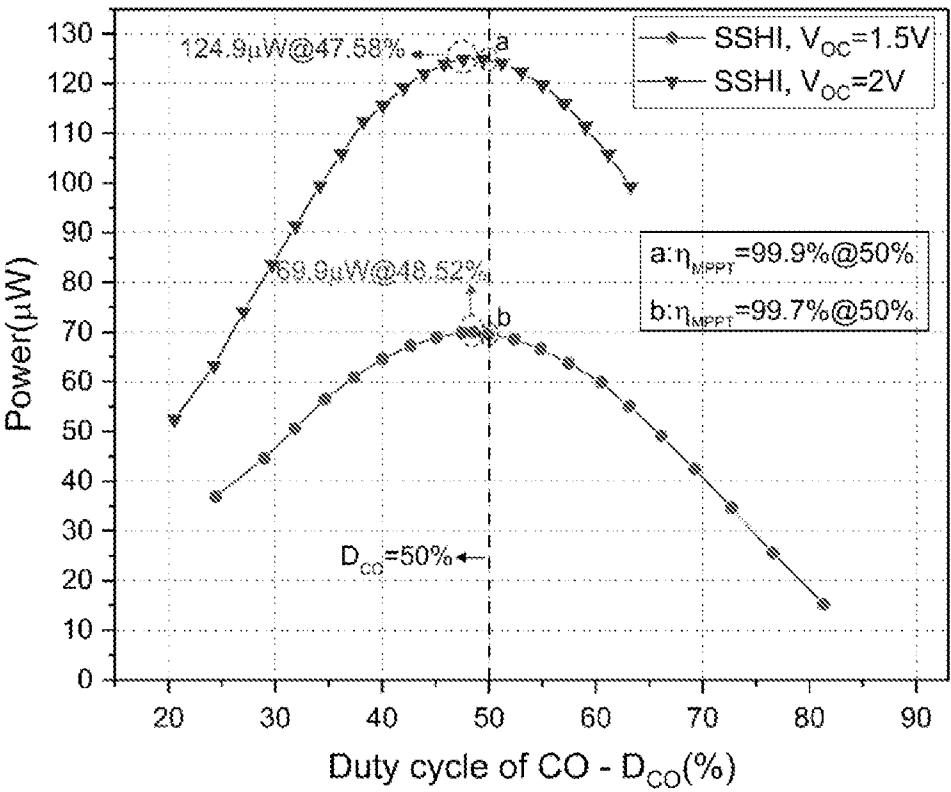


Fig. 7(a)

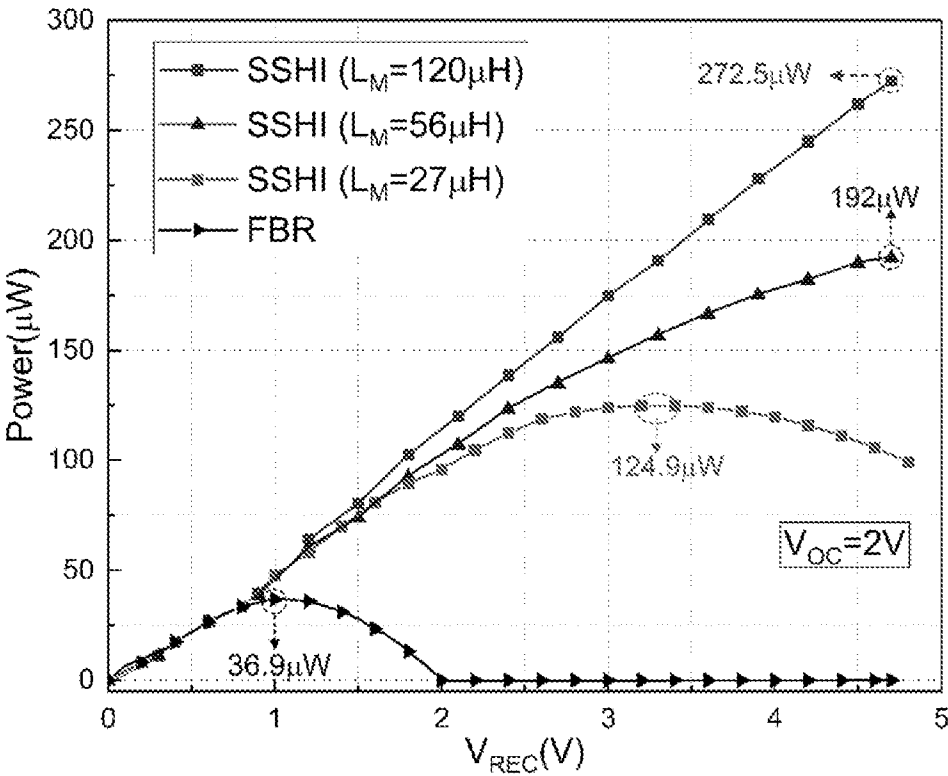


Fig. 7(b)

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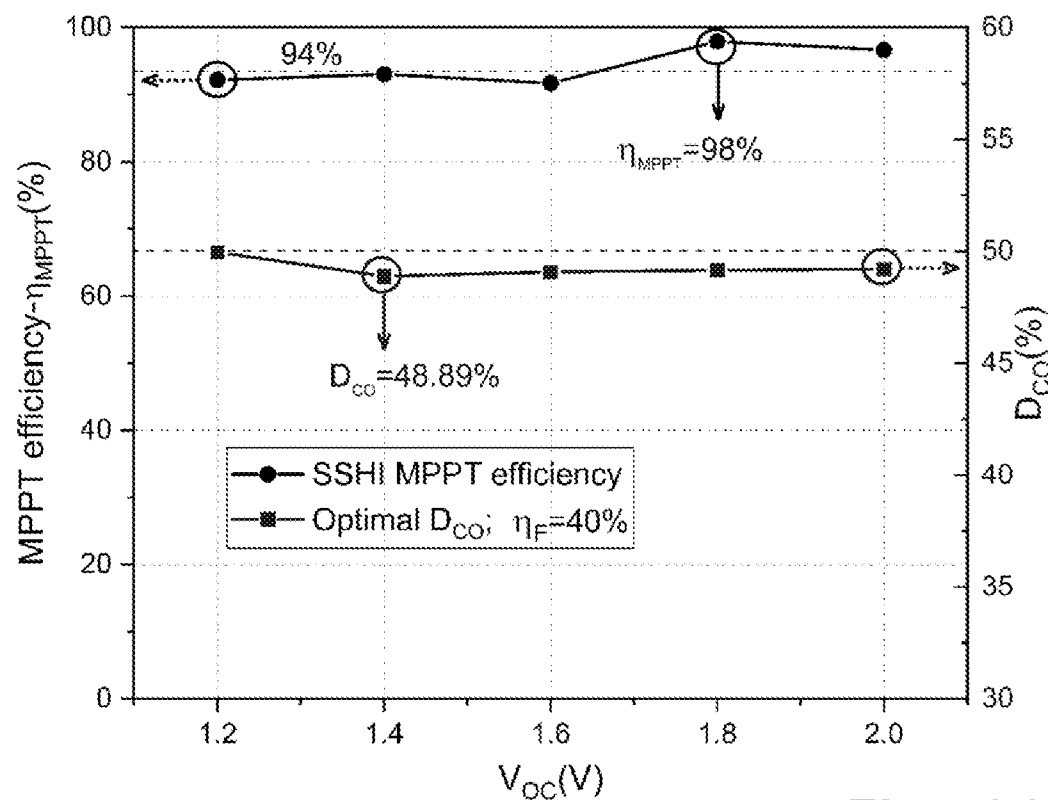


Fig. 7(c)

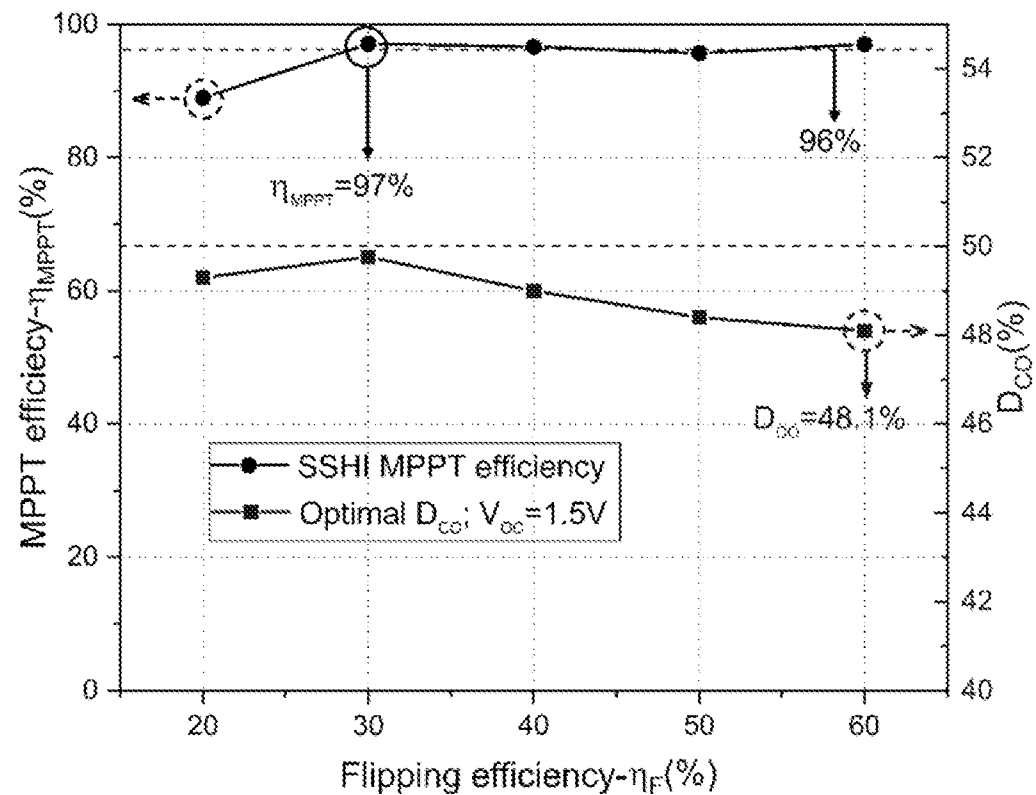


Fig. 7(d)

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	[3] ISSCC'14	[4] ISSCC'16	[5] ISSCC'19	[1] VLSI'19	[2] ISSCC'20	[6] ISSCC'22	This work
Technology (μm)	0.35	0.35	0.18	0.13	0.6	0.065	0.18
Technique	Comparator-based dual mode	P-SSHI	SPFCR	P-SSHI	PSECE	SECE	SSHI
Harvester Type	PEH-MIDE V21BL	PEH-MIDE V21B & V22B	PEH-MIDE PPA1021	PEH-MIDE PPA1021 & PPA1011	PEH	TEG/PV/PEH	PEH-S128-H5FR-1107YB
Piezoelectric Capacitance(nF)	11	26, 20, 9	22	20 & 100	24	24	42
Resonant Frequency(Hz)	100*	134.6-229.2	200	100-180	56	N/R**	220
MpPT Algorithm	FOCV	FOCV	FOCV	P&O	P&O	FOCV	Duty Cycle Based
Continuous MpPT	No	No	No	Yes	Yes	No	Yes
ADCCCA, /Sensor Required	N/R**	N/R**	Yes	No	Yes	Yes	No
VOC Sampling Required	Yes	Yes	Yes	No	Yes	Yes	No
Peak MpPT Efficiency	99%	N/R**	N/R**	97%	94%	80%	98%
Quiescent Current (μA)	3	N/R**	N/R**	0.9	0.3	N/R**	0.17
Dimension (mm^2)	5.5	1.3*	0.21	1.07	14	3.11	0.47
$P_{\text{CE}}/P_{\text{avg}}/\eta_{\text{r}}$	1X*@No	4.4X@89%/94%	6.5X-9.3X@89%	4.17X@86%	3.28X@No	3.2X@No	7.38X@82%

Fig. 8

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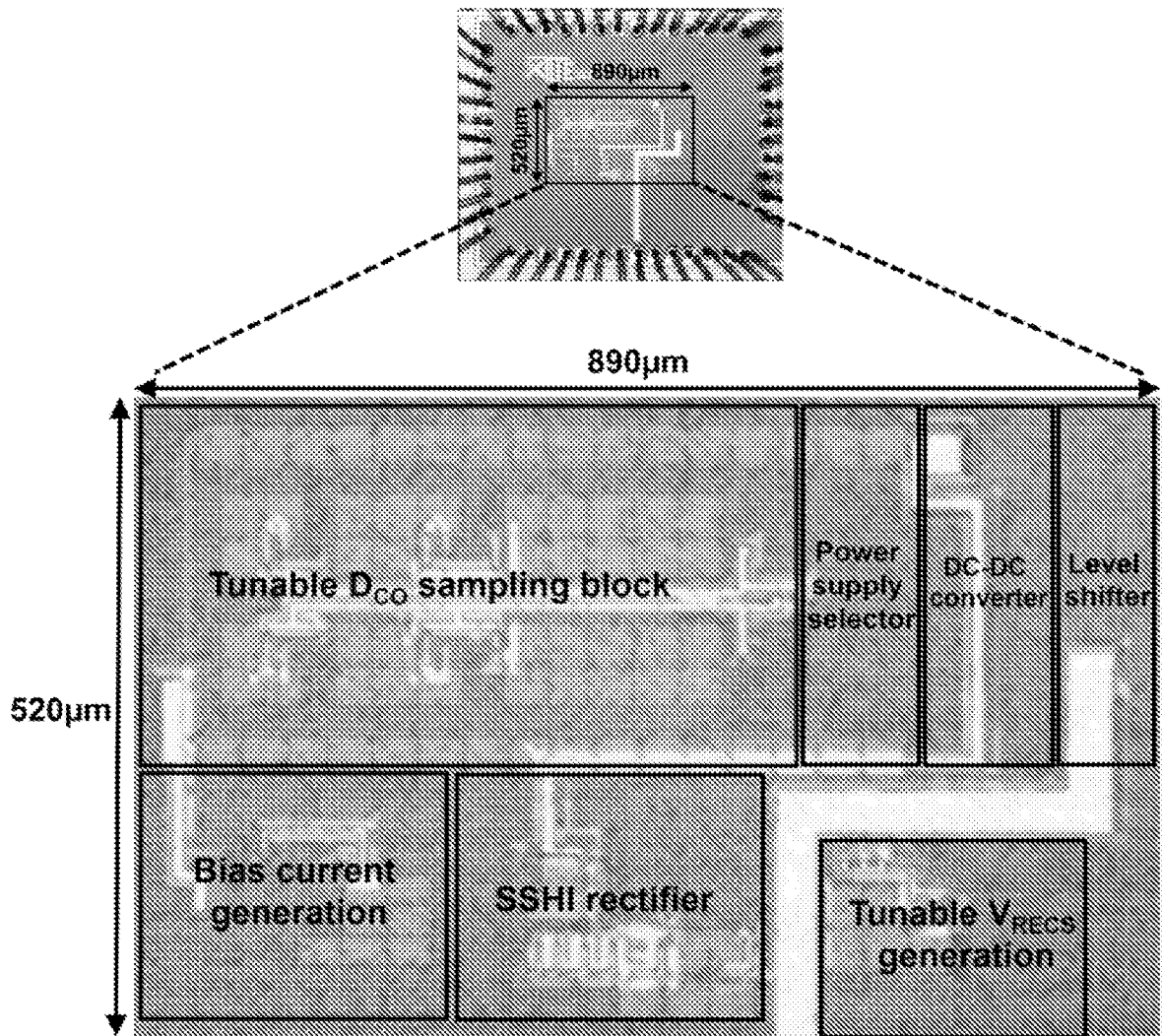


Fig. 9

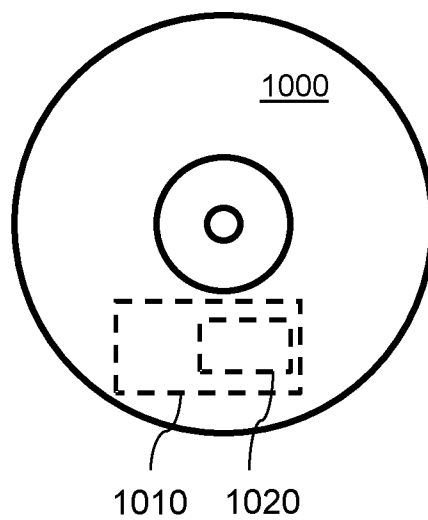


Fig. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2023/050668

A. CLASSIFICATION OF SUBJECT MATTER INV. H02J7/32 G05F1/67 H02J50/00 H02M3/156 ADD.		
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 H02M G05F		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2022/305272 A1 (MAKDISSI ALAA [FR] ET AL) 29 September 2022 (2022-09-29) figures 5, 7, 20, 22 paragraphs [0017], [0085] - [0150] -----	1-26
A	US 9 991 715 B1 (HUANG CHAO-JEN [TW] ET AL) 5 June 2018 (2018-06-05) figures 1, 6-9 column 2, line 66 - column 3, line 52 ----- -/--	1-26
☒ 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 another 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 15 February 2024		Date of mailing of the international search report 06/03/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Berger, Josef

INTERNATIONAL SEARCH REPORT

International application No

PCT/NL2023/050668

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LI SHUO ET AL: "A Piezoelectric Energy-Harvesting System With Parallel-SSHI Rectifier and Integrated Maximum-Power-Point Tracking", IEEE SOLID-STATE CIRCUITS LETTERS, IEEE, vol. 2, no. 12, 1 December 2019 (2019-12-01), pages 301-304, XP011762062, DOI: 10.1109/LSSC.2019.2951394 the whole document -----	1-26
A	DI LI ET AL: "Recent progress and development of interface integrated circuits for piezoelectric energy harvesting", NANO ENERGY, ELSEVIER, NL, vol. 94, 14 January 2022 (2022-01-14), XP086970770, ISSN: 2211-2855, DOI: 10.1016/J.NANOEN.2022.106938 [retrieved on 2022-01-14] the whole document -----	1-26

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/NL2023/050668

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		US 2022305272 A1	29-09-2022

US 9991715 B1	05-06-2018	NONE	
