Measurement, Instrumentation, and Sensors Handbook
Electromagnetic, Optical, Radiation, Chemical, and Biomedical Measurement
John G. Webster, Halit Eren

Energy Harvesting for Sensors: AC Harvesters

Publication details
Maria Teresa Penella, Oscar Lopez-Lapeña, Manel Gasulla
Published online on: 03 Feb 2014

Accessed on: 05 Oct 2023

PLEASE SCROLL DOWN FOR DOCUMENT

Full terms and conditions of use: https://www.routledgehandbooks.com/legal-notices/terms

This Document PDF may be used for research, teaching and private study purposes. Any substantial or systematic reproductions, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The publisher shall not be liable for an loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
11
Energy Harvesting for Sensors: AC Harvesters

Maria Teresa Penella
Unibiotica S.L.

Oscar Lopez-Lapeña
Universitat Politècnica de Catalunya

Manel Gasulla
Universitat Politècnica de Catalunya

11.1 Introduction ................................................................. 11-1
11.2 Radiofrequency Energy Harvesting .................................. 11-2
11.3 Mechanical Energy Harvesting ........................................ 11-6

References ............................................................................ 11-11

11.1 Introduction

Radiofrequency (RF) and mechanical energy transducers generate an alternating (ac) voltage and current that is proportional to the available power in the environment. There are other transducers (of different environmental energies) that also generate an ac signal. However, we have chosen these energies as the most representative in terms of the variety of energy conditioning circuits used. Other ac harvesters can use similar circuits and techniques to that presented in this chapter. Indeed, RF and mechanical energy sometimes benefit of the same energy conditioning circuit structures. However, note that each transducer has its own peculiarities that must be accounted for.

Signals generated by these transducers must be rectified in order to charge the battery or the (super) capacitor that powers the load (autonomous sensor). When using just a rectifying stage, the load fixes the working point of the harvester and the system is not optimized under all environmental conditions. Additionally, under some circumstances, the voltage coming from RF or mechanical energy transducers is quite low and needs to be stepped-up. One advantage of having an ac signal is that step-up transformers or rectifiers (among other step-up circuits) can readily be used to obtain the output voltage needed to power the autonomous sensor. Energy transducers and rectifiers can be modeled with a T even equivalent circuit that delivers maximum power to a matched resistive load. Consequently, several works have proposed maximum power point trackers (M PPTs) that bias the transducer, or the rectifier, at its maximum power point (MPP). M PPTs are more complex circuits that, if well designed, can highly improve efficiency at very low input powers.

This chapter describes two important ac energies (RF and mechanical) and the most used energy harvesting circuits.
11.2 Radiofrequency Energy Harvesting

RF signals are present in the environment as they are deliberately radiated by broadcasting stations and cellular phone antennas. The ambient available RF power must be harvested by means of broadband and/or circularly polarized antennas [1], because in most cases, there is either a broad range of frequencies and different polarizations or there is lack of detailed information on the ambient RF waves. Except for locations near transmitters, the available ambient power density \( S \) is in the nW/cm² range, which is too low to be useful. However, near transmitters, the power is much higher, and this is why deliberate RF power transmission on the industrial, scientific, and medical (ISM) application frequency bands has also become an alternative to power autonomous sensors [2]. In this case, \( S \) can be obtained from Equation 11.1:

\[
S = \frac{P_{\text{EIRP}}}{4\pi d^2}
\]  

(11.1)

where

\( P_{\text{EIRP}} \) is the effective radiated power, which is related to that of an isotropic radiator (an ideal antenna)
\( d \) is the distance from the transmitter

\( T \) is formula is for free-space propagation; for other scenarios, the power decays more rapidly with distance, unless the location features a structure that acts as a waveguide (e.g., in corridors). Additionally, there are other factors that affect \( S \), including multipath propagation and reflections; thus, calculating the real \( S \) requires accurate simulations or field measurements. Furthermore, the maximum \( P_{\text{EIRP}} \) for ISM frequency bands is regulated (for European regulations, see Annex 11.1 in [3]). The available power that the antenna can deliver to a matched load \( (P_{AV}) \) depends on \( S \) and on the effective aperture (area) of the antenna \( (A_e) \), as shown in Equation 11.2 (known as the Friis relation):

\[
P_{AV} = S \cdot A_e = S \frac{\lambda_{RF}^2}{4\pi} G_t = P_{\text{EIRP}} G_t \frac{\lambda_{RF}^2}{(4\pi d)^2}
\]  

(11.2)

where

\( A_e = \frac{\lambda_{RF}^2}{4\pi} G_t \)
\( G_t \) is the antenna gain
\( \lambda_{RF} \) is the wavelength

Equation 11.2 clearly demonstrates that the higher the frequency (\( \lambda_{RF} \) is inversely proportional to frequency), the lower the power range. In Europe, the most popular frequency bands for ISM applications are centered at 433 MHz, 868 MHz, and 2.4 GHz.

Figure 11.1 shows the building blocks of an RF energy harvester, encompassing at least an antenna, an impedance matching block, and a rectifier. In some cases, a low-pass filter can be used between the impedance matching and the rectifier in order to prevent harmonics from flowing back to the antenna and reducing voltage amplitude at the input of the rectifier. If a filter is used, an additional second impedance matching block is needed to match the filter output impedance to the input impedance of the rectifier. However, as these filters are not conventionally used in RF energy harvesters, we will not deal with these two blocks.

An RF transducer (antenna) can be modeled as a voltage source in series with an output impedance (Figure 1.1). Antenna shapes and dimensions vary widely, and several distinct antenna designs have been employed in RF and radiofrequency identification (RFID) harvesting applications. The series impedance basically comprises the radiation resistance \( (R_s) \), the loss resistance \( (R_{loss}) \), and a reactive part \( (X_{ant}) \). Depending on the antenna design, \( X_{ant} \) can be positive, thus presenting an inductive behavior.
**FIGURE 11.1** General block diagram of an RF harvester and the electrical equivalent model for an antenna.

(e.g., in loop-shape antennas) or negative, thus presenting a capacitive behavior (e.g., in patch antennas). The size of the antenna is inversely proportional to the desired resonant frequency. Despite this frequency dependency, some miniaturization techniques, such as high-dielectric substrates or meandered, bent, or tip-loaded structures, can be employed to minimize the final size of the system. The amplitude of the voltage generated on the antenna when matched ($\hat{v}_S$) depends on $P_{AV}$ and $R_s$ as

$$\hat{v}_S = 2\sqrt{2R_sP_{AV}}$$

(11.3)

Thus, at a given $P_{AV}$, $\hat{v}_S$ increases for a larger $R_s$. $\hat{v}_S$ must be relatively high in order to overcome the voltage drop of the diodes and reduce the losses from the rectifier. $P_{AV}$ depends on $A_s$ and $S$ and, therefore, depends on the antenna characteristics. If greater power is sought, voltages or currents can be added by connecting several antennas (in series and/or in parallel) to form an array; in this case, the antenna’s $A_s$ is increased at the expense of a larger physical area [1]. A single rectifying circuit for the whole array reduces the number of rectifying elements but can complicate array design. An antenna with rectifying and matching elements is called a rectenna. Rectennas can also be connected in series or parallel in order to add current or voltage; again, at the expense of greater effective area (and physical dimensions). The efficiency of the rectenna depends on input power, and for microwatt-level inputs is 20% maximum [1].

The transmitted power reaches its maximum when the antenna sees at its output an impedance that is the conjugate of its own impedance: $Z_{\text{ant}}^* = R_s - jX_{\text{ant}}$. In Figure 11.2, $Z_{\text{in}}$ ($R_{\text{in}}$ and $C_{\text{in}}$) is the equivalent input impedance of the rectifier and ensuing load. $Z_{\text{in}}$ should be adapted through a matching network (gray components in Figure 11.2) to present $Z_{\text{ant}}^*$ at the antenna (point A in Figure 11.2). This procedure is known as impedance matching. A properly matched design is as important as a well-designed antenna or rectifier. Numerous matching configurations are available. The choice of the specific configuration depends on the number of elements used for the matching and the way in which they are positioned. Nonetheless, to date, three main circuits have been proposed for RFID or RF harvesting [4]: a transformer (Figure 11.2a), a shunt inductor (Figure 11.2b), and an L network (Figure 11.2c). A shunt inductor matching does not boost the antenna voltage and can be used for high $R_s$ antenna for which $\hat{v}_S$ is relatively high (see Equation 11.3). As this is not always easy, a transformer or an L network can be used to boost the voltage generated on the antenna.

Rectifier circuits together with an output low-pass filter (in general a single capacitor) provide a direct current (dc) output voltage at the ensuing load. There are three main options for the rectifier:

1. A diode (which, together with the antenna, forms a rectenna) [1] Figure 11.3a
2. A bridge of diodes (or diode-connected transistors) (Figure 11.3b)
3. A voltage rectifier multiplier [5] (Figure 11.4 left shows a single stage circuit)
FIGURE 11.2 Typical matching network circuits for RFID or RF harvesting circuits: (a) transformer, (b) shunt inductor, and (c) L network. The matching network elements are shown in gray.

FIGURE 11.3 (a) Single diode and (b) diode bridge rectifiers.

All of these circuits are broadband (i.e., they exhibit the same rectifying characteristics in a broad band of frequencies). For kilohertz or megahertz frequencies, p–n diodes and transistors are used as rectifiers, whereas for microwave frequencies (>1 GHz), Schottky diodes (GaAs or Si type) are preferred, because they have shorter transit times. The rectification performance of the diode depends on its saturation current, its junction capacitance, and its conduction resistance. A large saturation current is sought, because it leads to a low forward voltage drop.

The diode (Figure 11.3a) and the diode bridge (Figure 11.3b) provide an output dc voltage to the load ($V_{out}$) whose value is lower than the peak value of the incoming signal. The voltage rectifier multiplier, as its name indicates, multiplies the peak amplitude of the incoming signal, Figure 11.4. At long distances (low $P_{AV}$ and, consequently, low $\hat{V}_S$; see Equation 11.3), the dc voltage level from diode or diode bridge rectifiers is not high enough to power an electronic circuit, so the voltage rectifier multiplier appears to be the best solution [5]. The output voltage of a voltage rectifier multiplier can be further multiplied by cascading several stages as in Figure 11.5.

FIGURE 11.4 A single stage of a voltage multiplier rectifier and waveforms during the transient.
The diodes of the rectifier can also be implemented using CMOS transistors connected as diodes, which is the case for most RFID tags [5]. Using rectifying elements with low threshold voltage and low reverse current will increase the sensitivity of the rectifier (i.e., the minimum input voltage at which the rectifier can work under given load requirements). To overcome the technological issues of traditional CMOS, researchers have proposed several rectifier designs. For example, to obtain transistors with very low threshold voltage, Curty et al. [6] employed the silicon-on-sapphire (SOS) CMOS process, and Karthaus and Fischer [7] used silicon-titanium Schottky diodes. Others have avoided using these relatively expensive processes by biasing the voltage at the gate of the transistor, which results in almost zero threshold voltage transistors [8,9]. RFID tags usually include the required number of stages that give the desired output voltage at the expected minimum input power, $P_{in}$.

P2110 and P1110 from Powercast [2] are two chips that integrate the rectifier and are designed for 50 Ω antennas and for the 850–950 MHz frequency band. The first one can deliver a regulated voltage from 1.8 to 5.25 V at input powers down to –11 dBm. Efficiency is around 10% at this power level and goes up to around 50% at higher power levels. The other circuit can more efficiently harvest input powers from –5 to 20 dBm.

Seen from the load, the rectenna (or the antenna plus any of the previously explained rectifiers) can be modeled with a T even equivalent as a dc voltage source ($V_{in}$) in series with a T even resistance ($R_{th}$). $V_{in}$ depends on environmental conditions and $R_{th}$ is constant for a certain range of input powers and generated voltages. Consequently, the system will deliver maximum power to a matched resistive load equal to $R_{th}$.

To boost the output voltage of the rectifier whenever it is too low, step-up switching converters can be used. Additionally, they can also be used to implement an MPP [10,11]. Considering the T even equivalent circuit of the rectenna, the simplest MPP technique emulates a fixed resistance equal to $R_{T}$. In this way, maximum power is extracted from the rectenna for a wide range of environmental conditions. A discontinuous conduction mode boost converter (Figure 11.6) with a simple open-loop controller emulates a resistor ($R_{eq}$) if its input voltage ($V_{in}$) is much lower than the output voltage ($V_{out}$). The average input current is proportional to $V_{in}$ with a proportional constant equal to $1/R_{eq}$ that depends on the duty cycle of the converter's transistor, $D$. $D$ depends on the converter timing parameters $T_{on}, T_{off}, k$, and $T_{d}$ from Figure 11.6. Using a fixed $D$ that leads to $R_{eq} = R_{T}$, the input voltage at the maximum power point, reaches $V_{MPPT}$ ($V_{T}/2$). Following this control scheme, the reported overall efficiency in [10] was 16.7% for a power density of 70 μW/cm² at the antenna ($P_{av}$ was around 2.5 mW) when connecting a thin-film lithium battery (4.15 V) at the output of the dc/dc converter.

In addition to the method previously explained, some of the techniques used for photovoltaic energy harvesting, such as the fractional open-circuit voltage (FOCV) MPP, can also be applied to RF harvesting. In RF energy harvesters, the proportional constant, $k$, of FOCV will be 0.5. In any case, the power consumption of the energy conditioning circuit must be in the microwatt level or below in order to achieve a net power gain.
11.3 Mechanical Energy Harvesting

Mechanical energy harvesting is a very active research topic that has spawned numerous reviews (e.g., [12]). It is based on kinetic energy [13], the sources of which include liquid or gas flow, vibrations, human activity, and pressure variations (e.g., acoustic noise and atmospheric pressure). Available power in flow energy increases cubically with an increase in the speed of the liquid or gas. Low-level vibrations occur in machinery, outdoor windows, and transport vehicles; they produce frequencies between 50 and 200 Hz and acceleration amplitudes between 1 and 10 m/s². Human activity can actively or passively generate kinetic energy. Active human power requires deliberate movement, whereas passive human power exploits common daily activities (e.g., heel strike while walking).

Mechanical energy can be coupled by one of the following conversion principles [14]: electrostatic, piezoelectric, and electromagnetic. Reported efficiencies are 0.32% [12], 0.5% (for polyvinylidene fluoride [PVDF]) to 20% (for lead zirconate titanate [PZT]) [15], and 6% [12], respectively. The generated signals are ac and must be rectified in order to power autonomous sensors. Figure 11.7 shows a general block diagram for the three types of conversion principles and the equivalent electrical models of the respective harvesters.

Electrostatic converters are based on variable capacitors. One plate is fixed and the other changes with the mechanical force, thereby changing the value of the capacitance. They are IC compatible as microelectronic variable capacitors can be fabricated via silicon micromachining techniques. Energy can be extracted via charge-constrained or voltage-constrained approaches. Charge and voltage are related through capacitance (Q = C · V); therefore, a change in capacitance produces variations in either voltage (charge constraint [16], Figure 11.8) or charge (voltage constraint [17], Figure 11.9). In both approaches, the extraction cycles are basically divided into three phases. In the first phase, the variable capacitor (C_{VAR}) is charged from an energy reservoir (can be a battery or a capacitor). Then, the harvest phase starts. In the charge-constrained circuit of Figure 11.8, the voltage of C_{VAR} increases as the distance between the plates increases (capacitance decreases) and charges a temporary capacitor (C_s). If the diodes are replaced by transistors, less power will be lost during this phase; however, the control signals will need to be synchronized with the mechanical movement. In the voltage-constrained circuit of Figure 11.9,
the energy reservoir is directly connected to the harvester and $V_C = V_{BAT}$ during the harvest phase. Thus, current flows to the energy reservoir as the capacity of the harvester decreases (distance between the plates increase). For the charge-constrained scheme, the third phase is performed after several harvest phases. In this phase, the energy in $C_S$ is transferred to the main energy reservoir unit ($C_{RES}$) through a buck converter (flyback phase), and afterward, the process is started again. In the voltage-constrained scheme, after the harvest phase, the remaining energy in the variable capacitor can be recovered (recovery phase). Nonetheless, this energy is very small and not worthy to extract.

However, these converters have several drawbacks: They need a power source reservoir for starting the extraction cycles, and in the charge constraint scheme, they operate at high voltages, which limit their implementation to more expensive integration processes [18].

Reversible electric polarization in response to strain from mechanical stress is called the piezoelectric effect. Piezoelectric materials are anisotropic: their properties vary according to the direction of force and the orientation of the polarization and the electrodes. Several operational modes can be employed...
for piezoelectric harvesters, the most widely used of which are modes 33 and 31. Mode 33 is used to extract energy from impact or when harvesting energy from passive human power. Mode 31 is more suited for cantilever structures with a proof mass at the free end. Cantilevers are usually bimorphic structures comprising two piezoelectric materials bound together, with a shim in between them. For power extraction, cantilevers typically operate at their resonant frequency. Piezoelectric transducers can be electrically modeled as an ac current source ($I_{\text{piezo}}$) in parallel with a capacitor ($C_{\text{piezo}}$) [19] (Figure 11.7). The main challenge with piezoelectric harvesters is integrating them into an IC.

The maximum voltage at which $C_{\text{piezo}}$ will be charged (piezoelectric open-circuit voltage, $V_{\text{POC}}$) is generally in the volt level and can be directly connected to conventional bridge rectifiers (Figure 11.3b) without significant power losses. $V_{\text{POC}}$ depends on $I_{\text{piezo}}$ (determined by the displacement achieved), the angular frequency $\omega$ of the movement, and $C_{\text{piezo}}$ (see Equation 11.4). In this case, $V_{\text{POC}}$ is usually much higher than the diodes voltage drop ($V_D$) and must at least be $2V_D$ in order to extract energy from the transducer. For example, a piezoelectric energy harvester such as Volture [20] from Mide (tuned to work at vibrations frequencies between 80 and 175 Hz) can produce several milliwatts at 9.8 m/s² vibration with a conventional rectifier. $V_{\text{POC}}$ depends on $I_{\text{piezo}}$ (determined by the displacement achieved), the angular frequency of the movement and $C_{\text{piezo}}$:

$$V_{\text{POC}} = \frac{I_{\text{piezo}}}{\omega \cdot C_{\text{piezo}}}$$

(Equation 11.4)

Nonetheless, for microscale implementations or under certain environmental conditions, the output voltages can also be relatively small. Furthermore, more power can be generated if some charge is injected to the piezoelectric element before force is done against it in order to increase the force it posses to the movement. Thus, other circuits have been proposed [21]:

- Synchronous switched extraction circuits that extract all the generated energy from $C_{\text{piezo}}$ at lower voltages than the bridge rectifier
- Circuits that inject some charge to the piezoelectric element before force is done against it

In the synchronous switched extraction circuit (Figure 11.10), the charge is accumulated in $C_{\text{piezo}}$ until $I_{\text{piezo}}$ crosses zero (at the maximum displacement of the piezoelectric transducer), then the switch (S) is closed and charge is extracted with a resonant $LC$ circuit. The switch S is closed for a period that
corresponds to half the cycle of the resonant frequency of the LC circuit allowing the extraction of all the charge in $C_{\text{piezo}}$ whenever the output voltage ($V_{\text{out}}$) is carefully chosen. The discharge time of $C_{\text{piezo}}$ should be very small related to the period of the movement. Diode $D$ is used to allow the current in $I$ (if any) freewheel to $C$ once $C_{\text{piezo}}$ has been fully discharged. The circuit can handle lower $V_{\text{POC}}$, and contrary to the bridge rectifier circuit, the voltage in $C_{\text{piezo}}$ is zero at the end of the charge extraction; thus, more power is harvested. The circuit is feasible whenever $V_{\text{POC}} > V_D$.

There are two main types of circuits that inject charge to the piezoelectric element: synchronous, switched harvesting with inductor (SSH1) and prebias circuits.

In SSH1 circuits, there is an initial generation phase that stores charge in $C_{\text{piezo}}$, and afterward an inductor, in parallel or series (Figure 11.10) with the piezoelectric transducer, is switched at the zero crossings of $I_{\text{piezo}}$ in order to invert the polarity of $C_{\text{piezo}}$ (charge-flipping phase). In parallel SSH1 configuration, $V_{\text{POC}}$ can be lower than $V_D$.

There are several implementations of prebias circuits, the simplest uses switches in an H bridge configuration (Figure 11.10). There are three phases for each semiperiod of $I_{\text{piezo}}$: Firstly, S1 and S4 are closed and $C_{\text{piezo}}$ is precharged to the reservoir voltage; then, they are opened and the harvest phase starts; and afterward, when $I_{\text{piezo}}$ reaches zero, S1 and S4 are closed again and $C_{\text{piezo}}$ is discharged to 0 V through an LC resonant circuit. In the other semiperiod, the same phases are repeated with diodes S2 and S3. These circuits allow extracting more power from the harvester than SSH1 circuits at the cost of more control overhead because the rectification bridge is implemented with switches.
In any case, there is an MPP at which extracted power is maximal. As happened with RF harvesting circuits, this MPP corresponds to an optimal resistance load in parallel to the output capacitor of the rectifier. Thus, a resistor emulator circuit as that described in Figure 11.6 has also been described for piezoelectric harvesters [22].

In some cases, resonant matching networks have also been used to boost the voltage at the input of the rectifier [23]. This work uses a commercial piezoelectric energy harvesting circuit, LTC 3588 from Linear Technology, which integrates a full bridge rectifier. Linear has indeed several energy harvesting circuits for piezoelectric energy harvesting that work with input voltages between 2.7 and 20 V and can output voltages between 1.8 and 5 V with current consumptions below one microampere.

Electromagnetic induction, based on Faraday's law (see Equation 11.5), refers to generation of a voltage \( V_{en} \) in a conductor (typically, a coil) located within a magnetic flux \( \phi \), usually generated by a permanent magnet. The generated voltage depends on various factors, including the strength of the magnetic field, the velocity of the relative motion between the coil and the magnet, and the number of turns in the coil. Electromagnetic energy transducers can be electrically modeled as low-level ac voltage sources with low series impedance (Figure 11.7):

\[
v = -\frac{d\phi}{dt}
\]  

(11.5)

Since magnets are quite difficult to integrate into ICs, integrated prototypes of these transducers show very low output powers. Thus, type of harvester is best suited for high-frequency and low-amplitude vibrations. Some commercially available energy harvesters at macroscale (e.g., the Perpetuum Ltd. [24]) are based on this principle.

Even for macroscale implementations, the generated voltage can usually be around hundreds of millivolts [19]. Bridges or single diodes could be used as the rectifier (Figure 11.3). In that case, the rectifying elements can be implemented with diode-connected transistors that will present lower threshold voltages. However, the output voltage of the rectifier will be lower than the peak value of the input signal (see Equation 11.2), and thus, it will still need to be stepped-up by using, for example, a boost dc/dc converter.

Voltage can also be boosted by using transformer matching circuits before rectification. In Figure 11.11, the voltage of the harvester is boosted by the turns ratio of the transformer, and afterward, each semiperiod of the ac signal is rectified with one of the diodes. One of the major challenges of this circuit is IC integration as transformers are quite difficult to integrate into ICs.

The voltage multiplier rectifier (Figure 11.4) or modified versions of this circuit can also be used to rectify and boost the output voltage of the harvester. The lack of magnetic components makes the voltage multiplier rectifier a good option for IC integration.

More complex circuits such as dual polarity boost converters (Figure 11.12) have also been proposed [19]. Here, each converter is used to boost and rectify one of the two semiperiods of the generated

**FIGURE 11.11** Circuit to boost the output of an inductive mechanical harvester by using a step-up transformer prior to rectification.
signal. Rectification is achieved by the alternate activation of one of the two converters. The circuit requires some control overhead.

Finally, MPP circuits that make the harvester work as if it had an optimal resistor at its output, through resistor emulation as in RF (Figure 11.6) or by setting the working voltage to half the harvester open-circuit voltage ($V_{OC}$) [25], have also been proposed. In [25], they used switched capacitors to fix the harvester's working voltage at 0.5 $V_{OC}$, where $V_{OC}$ needs to be periodically sampled.

The trend in energy harvesters is to integrate several energy conditioning circuits into the same chip in order to extract energy from multiple energy sources. Several commercial products and scientific works have recently appeared. Nevertheless, these circuits use the most suitable energy conditioning circuit for each energy source because, as can be deduced from this work, each transducer has its peculiarities. A commercial product from Cymbet, CBC915 [26], can be used indistinctly with different energy harvesters and make them work at their MPP. Furthermore, in [27], they propose a circuit that accepts energy from optical, thermal, and mechanical energy harvesters at the same time and makes all the harvesters work at their MPP for a wide range of environmental conditions. For the mechanical harvester, they used a conventional rectifier and then a buck-boost converter makes this system work at its MPP.

References