Piezoelectric Energy Harvesting: A Developing Scope for Low-Power Applications

Oshin Garg, Sukesha Sharma, Preeti and Pardeep Kaur

1 Introduction

With the progress in wireless technology and low-power electronics, wireless sensors can be used in almost every field. Some of the applications of wireless sensor networks are structure health monitoring, automation, robotics swarm, and military applications. However, these devices require their own energy source which in most cases is the conventional battery. The lifetime of these batteries is limited and they need to be replaced time to time. The task to replace the batteries is very challenging because most of the wireless sensors are placed in remote areas. This hinders the working of wireless sensors and restricts its use. Energy harvesting is one of the best possible solutions to extend the lifetime of wireless sensors and other portable low-power electronic devices. Energy harvesting will make it possible to use these devices in near future to much greater extent [1]. Energy harvesting is the technique to use the available energy from the environment and convert it into electrical energy to power the low-power electronic devices such as wireless sensors. The diverse sources of energy can be solar energy, electromagnetic waves, thermal energy, wind energy, kinetic energy, etc. Energy harvesting is an attractive alternative for the batteries and can be used for various energy applications ranging from low power to high power [2, 3]. In this paper, various energy harvesting techniques have been discussed. Organization of the paper is as follows: in Sect. 2 various energy harvesting techniques have been discussed. In Sect. 3, piezoelectric energy harvesting technique is introduced. In Sects. 4–6 transducer design, rectifier circuit, and storage units have been discussed respectively. Section 7 summarizes the study.

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2 Different Approaches to Energy Harvesting

The energy harvesting techniques can be classified based on the sources of energy. The different energy sources for energy harvesting and their working principle have been shown in Fig. 1.

The energy can be harvested from solar energy by photovoltaic principle. The photovoltaic principle is the creation of voltage and current in the semiconductor material when it is exposed to light [4]. In solar energy harvesting, photovoltaic cells are used that converts the incoming light or photon into electricity. This type of energy harvesting is known as photovoltaic energy harvesting [5]. The energy can also be harvested from temperature difference by the principle of 'seeback effect', which states that when there is a difference in the temperature between two junctions made up of conducting materials a voltage is developed between them. This type of energy harvesting technique is known as thermal energy harvesting [6]. The energy can also be harvested from RF energy available in the environment due to various mobile communication services such as GSM by electromagnetic principle. This type of energy harvesting is known as RF energy harvesting [7]. Another approach to harvest energy is from motion or vibrations. The vibrational energy can be harvested by three principles, i.e., electrostatic, electromagnetic, and piezoelectric. The electrostatic principle is based on changing the capacitance of a capacitor using a source of vibration. Vibration separates the plates of a charged variable capacitor, and hence the mechanical energy is converted into electrical energy. The energy harvesting using this principle is known as electrostatic energy harvesting [8]. The electromagnetic principle is based on the fact that a motion in the magnet inside a copper coil induces a voltage in the coil due to change in the magnetic field. The energy harvesting using this principle is known as
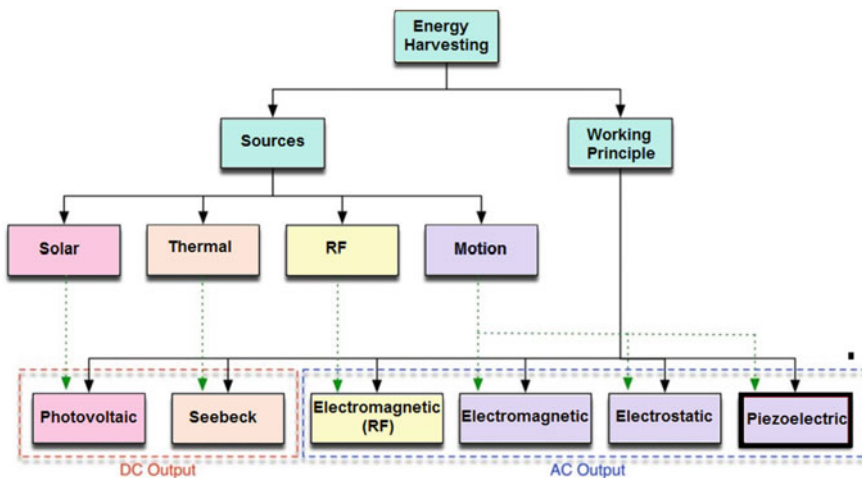

Fig. 1 Energy harvesting techniques and their working principle [38]

electromagnetic energy harvesting [9]. The piezoelectric principle is based on the fact that when a force is applied to piezoelectric materials they generate an electrical potential due to charge separation and vice versa. The energy harvesting using this principle is known as piezoelectric energy harvesting [10].

The above-discussed energy harvesting techniques can be classified as high-power energy sources and low-power energy sources based upon the power output. High-power energy sources (or macro sources) are the sources that give output power in kilowatts are, e.g., solar, wind, etc. [11]. Low-power energy sources (or micro) are the sources that produce an output power in the range of milliwatts, e.g., vibration, motion, heat, etc. [11]. Depending upon the power requirement of any application, one can select one of the approaches mentioned above. Piezoelectric energy harvesting is classified under low-power energy harvesting as it produces power in the range of milliwatts. Piezoelectric energy harvesting circuit is least complex and is easy to analyze as compared to other low-power vibrational energy harvesting approaches, hence it can be used to provide energy to low-power wireless devices. This paper is focused on piezoelectric energy harvesting.

3 Piezoelectric Energy Harvesting

Piezoelectric crystals are made up of materials, which are also called ferroelectric which have a property that when a force is applied on such materials they generate an electrical potential due to charge separation. This effect is known as the piezoelectric effect. Piezoelectric energy harvesting is based on the principle of the piezoelectric effect. It is a reversible process, i.e., when a voltage is applied across such crystals their shape is changed [12]. Some examples of piezoelectric materials are PZT (lead zirconium titanate), PVDF (polyvinylidene fluoride). Figure 2 shows the piezoelectric effect.

Piezoelectric energy harvesting circuit consists of three main components: transducer, rectifier, energy storage unit. The first step of piezoelectric energy harvesting circuit is to convert mechanical force or vibrations into electrical energy by means of transducer or energy harvester. It consists of piezoelectric ceramic,

Fig. 2 Piezoelectric effect [12]
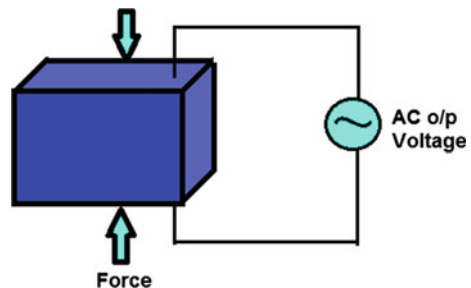
elastic body, and a tip mass. This simple structure of the harvester produces large strain when subjected to vibrations and can convert mechanical energy into electrical energy. This output is AC, i.e., alternating current and it needs to be converted to DC, i.e., direct current by using a rectifier. The last step of the harvesting circuit is to store this energy for future use to power electronic devices [13]. There are various factors such as the physical design of transducer, operating frequency, etc., that decides the performance of the harvesting circuit. These parameters have been discussed in detail. Piezoelectric transducer has been discussed in next section.

4   Piezoelectric Transducer

The transducer is a device that converts one form of energy into another. A piezoelectric transducer converts the mechanical vibrations or forces into electrical energy. It gives an AC output voltage whose magnitude is proportional to the applied force. There are some parameters that need to be considered while designing a piezoelectric transducer to maximize its output power. These parameters are discussed below.

4.1   Choice of Material

The material of a piezoelectric crystal is an important parameter that needs to be considered before designing a piezoelectric transducer. The piezoelectric material includes bulks, thin films, and nanostructure materials. Bulk piezoelectric materials include PZT (lead zirconate titanate) and related compositions. They have excellent piezoelectric properties but they are brittle in nature. Mostly single-crystal piezoelectric materials have better piezoelectric behavior than polycrystalline ceramics. Some of the single crystals are PZN-PT and PMN-PT, which have outstanding piezoelectric properties and can produce much higher power output than ceramics but they have been hardly used for energy harvesting because of high cost and difficulty in fabrication [14]. MEMS technology is another widely used technology because it could provide high flexibility and strain in the material. Also, materials fabricated by MEMS technology can be used in microelectronics and require very less power [15–18]. Flexibility tends to increase the usage of piezoelectric crystals and they can be used under large strain. To achieve flexibility nano- and microstructure materials and thin films have been used with polymers. In 2006, Zhong Lin Wang first introduced piezoelectricity in ZnO which were highly flexible [19]. PZT material has much larger piezoelectric coefficient hence generate larger output power [20, 21]. Hence, researchers worked on flexible piezoelectric structures using PZT but their synthesis was difficult. Some of the PZT-based flexible materials are nanotubes, nanorods, nanowires, thin films, etc. Different piezoelectric materials have different behaviors, for example, some are brittle but provide large

output power, some are flexible but generate less power. Depending upon the application, working environment of transducer and power requirements material for the piezoelectric transducer can be selected. Various piezoelectric materials have been investigated and many research papers have been published. PZT material has been most widely used for energy harvesting because of its advantages over other practically available piezoelectric materials and it produces maximum power for random vibrations. Although PZT continues to be the best choice it contains lead which is not environment-friendly. Many researchers are researching for the lead-free piezoelectric material that could replace the PZT material. None of the presently available non-lead materials match the performance of PZT but several materials have been considered having advantages of low densities, high coupling factor, high mechanical strength. Some of the lead-free piezoelectric materials are barium titanate (BT), sodium bismuth titanate (NBT), potassium bismuth nitrate (KBT), bismuth ferrite (BFO), quartz (SiO_2), etc. [22].

4.2 Choice of Structural Design and Loading Mode

Another parameter that should be considered while designing a piezoelectric transducer is its structure and the loading mode. Based on the number of active layer, i.e., layers of piezoelectric material there are two possible structures namely, unimorph and bimorph. Unimorph structure of a piezoelectric transducer has one layer of piezoelectric material (active layer) and another of elastic material (passive layer). A bimorph structure of a piezoelectric transducer has two layers of piezo material (active layers) and a layer of elastic material (passive layer in between). Figure 3 shows unimorph and bimorph structures of a piezoelectric transducer [23].

Loading mode defines the direction of force applied to the piezoelectric crystal and the direction of which output is taken or measured. Although there are many possible loading modes there are two main loading modes which are used for energy harvesting purpose, i.e., 3-1 loading mode and 3-3 loading modes. In 3-1 loading mode, the direction of electric field is perpendicular to the direction of force applied. In 3-3 loading mode, the direction of electric field is parallel to the direction of force applied. Figure 4 shows 3-1 and 3-3 loading modes for a piezoelectric transducer [24].

With different loading modes and structures, maximum power is obtained is always different [25]. This comparison has been shown in Table 1. 3-3 loading mode always produces more power output [26].
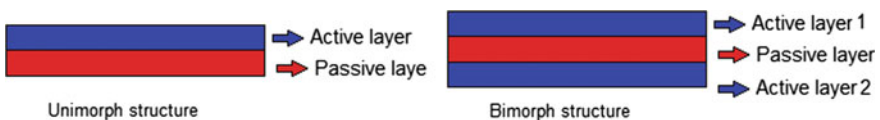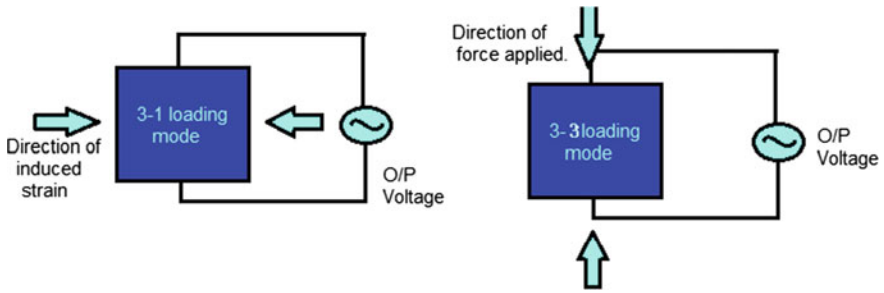

Fig. 3 Unimorph and bimorph structures [23]

Fig. 4 3-1 and 3-3 loading modes [24]

Table 1 Power obtained at different loading modes and structures [25, 40]

Loading mode	Structural design	Average output power (nW)
3-1	Unimorph	3.9
3-1	Bimorph	9.6
3-3	Unimorph	21.42
3-3	Bimorph	22.47

4.3 Type of Fixation

Another parameter for the design of transducer is the type of fixation which defines the placement of piezoelectric crystal. There are mainly two types of fixations simple beam fixations, cantilever beam fixations. In simple beam, both ends are supported and the force is applied at the center of the beam. In cantilever beam, one end is fixed and another end is free and is set to vibrations/force is applied at the free end. The cantilever beam is widely used to obtain high power from piezo-electric transducer because it produces larger strain [27]. Figure 5 shows simple beam and cantilever beam fixations.
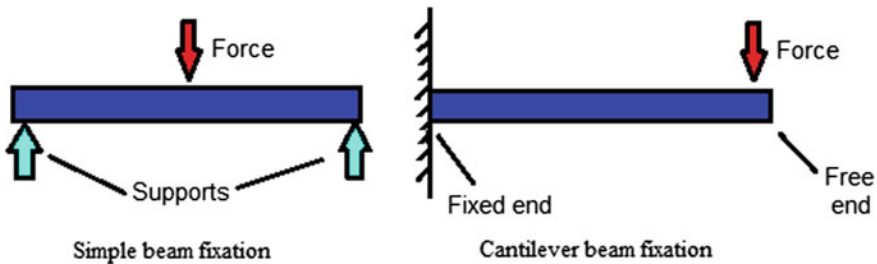

Fig. 5 Simple beam and cantilever beam fixations [27]

4.4 Impedance and Resonance Frequency Matching

The internal impedance of the piezo transducer is given by Eq. (1).

$$z = 1/(2\pi f_n C_{Piezo}) \tag{1}$$

where z is the input impedance, f_n is the natural frequency, C_{Piezo} is the capacitance of piezo transducer. According to the maximum power transfer theorem, this impedance should be matched with load impedance to transfer the maximum power to the load [25, 28].

To maximize the output power, the cantilever beam is operated on resonance frequency or the natural frequency of oscillations. Resonance frequency for a cantilever beam is given by Eq. (2).

$$f_r = v_n^2/2\pi L^2 \sqrt{(YI/mw)} \tag{2}$$

where f_r is the resonance frequency, $v_n = 1.875$ is the eigenvalue, L, m, w are the length, mass, width of the cantilever beam, respectively, I is the moment of inertia, Y is the Young's modulus [18, 24].

4.5 Addition of Mass at the Free End of Cantilever Beam

It has been shown experimentally that on increasing the mass at the tip of the cantilever beam the output power increases. This can also be seen from Eq. (2), that resonance frequency is inversely proportional to the mass at the tip of the cantilever beam. Hence, the resonance frequency can be decreased by adding a mass at the free end of the cantilever which is easier to achieve and hence the output power will increase. When the cantilever beam is excited at the resonance frequency the output

Fig. 6 Effect of addition of mass [28]
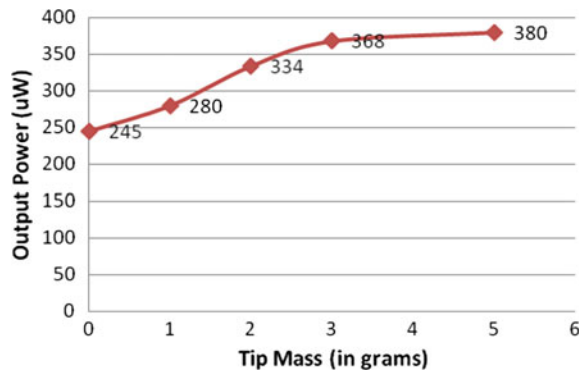
power will be maximum. Figure 6 shows the effect of adding mass at the tip of the cantilever beam on the output power.
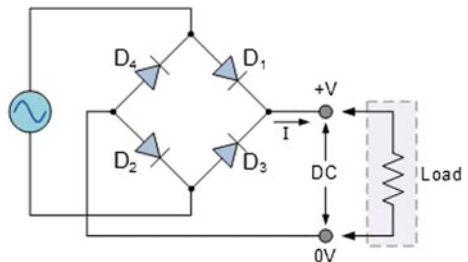
5   Rectifier Circuit

Rectifier circuits converts alternating current/voltage (AC) into direct current/voltage (DC). Alternating current (AC) is the current which reverses its direction periodically and direct current is the current that flows only in one direction (DC). The output of the transducer is AC and it needs to be converted into DC for further processing or storage thus rectifier circuit is required. The rectifier converts AC signal into DC. This process is called rectification. For low-power level from the piezoelectric microgenerator, rectification scheme must be chosen carefully so that output from the piezoelectric transducer is efficiently transferred to the load. Conventional rectifier circuits have been discussed below.

5.1   Bridge Rectifier

It is the most widely used rectifier circuit as it produces full-wave rectification and output of the bridge rectifier gives smaller output voltage ripples (i.e., unwanted AC variations in the DC signal). It consists of four diodes placed in the form of a bridge. Figure 7 shows a conventional bridge rectifier. There are a pair of two diodes (D_1, D_2, and D_3, D_4) connected in series and only one pair diodes allows current to pass through them during one cycle of AC input [29]. BAT 754 series Schottky diode is most suitable for bridge rectifier circuit as it has very low forward voltage and also has low diode capacitance. The normal diode has a voltage drop of around 0.6–1.7 V whereas Schottky diode has a voltage drop between 0.15 and 0.45 V [30].

Fig. 7 Full-wave bridge rectifier [29]

5.2 Voltage Doubler Rectifier

It is a rectifier circuit which takes the AC input and produces twice the input voltage at the output in the ideal case. The circuit of double voltage rectifier consists of two diodes (D_1, D_2), two capacitors (C_1, C_2), and an oscillating AC input voltage (V_{ac}). The diodes and capacitors work together efficiently to give almost double output than the peak to peak value of the input. Figure 8 shows a voltage doubler rectifier circuit [31].

5.3 Synchronous Rectifier

Although Schottky diode continues to be the best choice for the design of rectifiers, synchronous rectifiers are being studied because it provides very high efficiency. Different circuits using active devices such as MOSFET and FETs has been proposed. One of the proposed synchronous rectifiers is active cross-coupled rectifier with the synchronized switch. It has two active diodes instead of conventional passive diodes [32]. Figure 9 shows the efficiency comparison of synchronous rectifier using FETs and bridge rectifier using Schottky diode. Synchronous rectification is used for voltages above 5 V or currents below 10 A and it is normally used in the applications which work at the frequency less than 300 kHz. The Schottky diode can be used for high voltages and high output current [33]. It has been found that the power conversion efficiency of the conventional diode bridge rectifier is 38.08% and active rectifier with synchronous switches is 93.3% respectively [34].
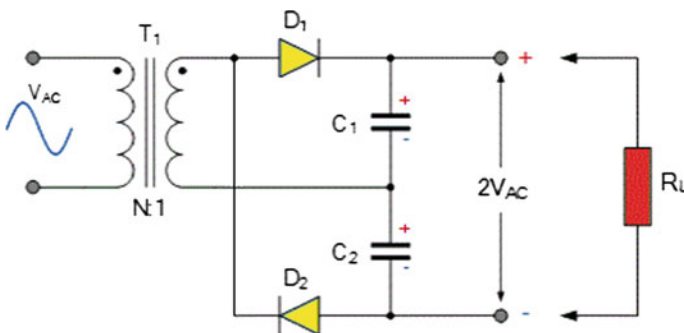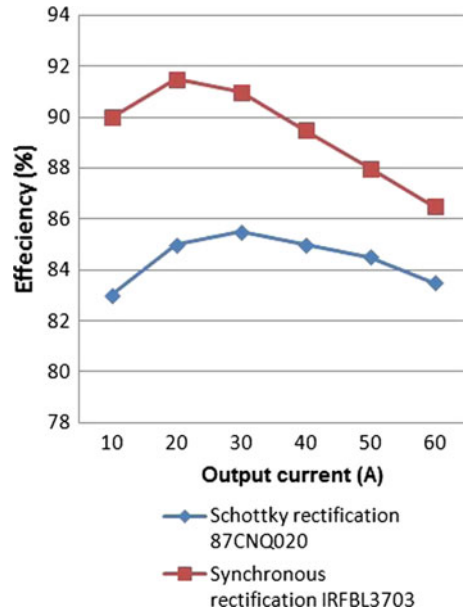

Fig. 8 Full-wave voltage doubler rectifier [31]

Fig. 9 Efficiency versus output current for FET and Schottky diodes [33]

6   Energy Storage Unit

There are mainly two types of energy storage units that are being used namely batteries and supercapacitors. Many batteries have been made till now that can be used to store energy to power mobile electronic devices. There are three main cells/batteries that are used in wireless sensor networks namely Nickel–Metal Hydride (NiMH), Lithium Ion (Li-Ion), and Lithium Polymer (Li-polymer). Different batteries have different characteristics such as charge density, voltage, charging time, etc. These parameters have been discussed in Table 2. Based upon these parameters, we can choose a battery for desired application.

Figure 10 shows the comparison between different batteries namely lead–acid (2 V), nickel cadmium (1.2 V), nickel–metal hydride (1.2 V), lithium-ion (3.6 V) and lithium polymer (3.7) based on the energy density and specific energy of different batteries.

Another type of storage unit used in energy harvesting circuit is supercapacitors. Capacitors are designed with different power levels and different materials example glass, ceramics, metal films etc. Supercapacitors are the capacitor with very high power density and extremely high energy density hence they are sometimes called a mechanical battery. They have very small size as compared to conventional batteries. They have a very less charging time. Supercapacitors can be classified as faradic and non-faradic supercapacitors [35]. Faradic capacitors charge faradically by transferring charge between the electrolyte and electrode. There two widely used conducting materials for making electrode namely conducting polymers such as polyacetylene

Table 2 Parameters of a battery [41]

S. No.	Parameter	Explanation
1	Battery voltage	It is the voltage of the cell
2	Capacity	It is the amount of electrical charge that can be stored in the battery
3	Specific energy	It is related to the volume and is measured in energy per weight
4	Energy density	It is the amount of energy that can be stored in the battery. It is measured in energy per volume
5	Internal Resistance	It specifies the ability of a battery to manage a specific load
6	Self-discharge	It points to the aging effect of the battery and leakage with time
7	Recharge cycles	It specifies the no. of times a battery can be charged till its performance degrades
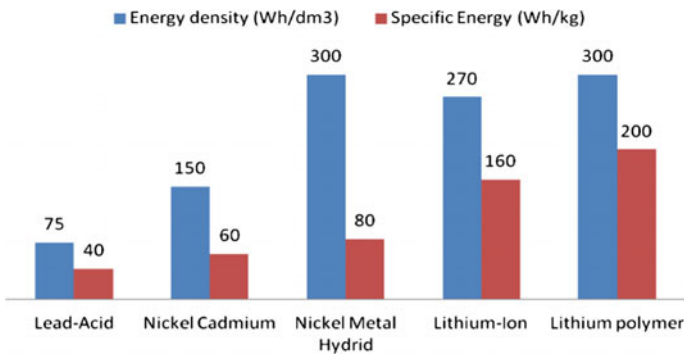
Fig. 10 Energy density and specific energy of various batteries [39]

and metal oxide such as ruthenium oxide [36]. Non-faradic capacitors charge non-faradically that is there is no transfer of charge between the electrolyte and the electrode. Non-faradic capacitors are made using carbon electrodes [37].

7 Conclusion

The following conclusions can be drawn from the literature survey:

1. Cantilever beam transducer design using bimorph structure, 3-3 loading mode produces more output power. The output power can be further increased by adding mass at the tip of the cantilever beam. To maximize the power output, load impedance should be matched with the input impedance and the cantilever should be excited at the resonant frequency.
2. There are three major types of rectifier circuits: voltage doubler rectifiers, bridge rectifiers, and synchronous rectifiers. Although conversion efficiency of

synchronous rectifiers is more than the conventional bridge rectifiers, diode bridge rectifies are most commonly used in energy harvesting circuits due to its simplicity. In diode bridge rectifier BAT 754 series Schottky diode is used because of its very low voltage drop.

3. In comparison between the rechargeable batteries and supercapacitors, the rechargeable batteries are preferred as they have higher energy stored per unit weight and slow discharging rate. Supercapacitors are used where fast charging is required.

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