A Review on Techniques and Challenges of Energy Harvesting from Ambient Sources

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Abstract— Energy harvesting is a process of generating energy from various ambient sources. Vibration energy harvesting has been a dynamic field of studying interest over the past decade due to the mitigation of power crisis from society. To harvest electrical energy various energy harvesting techniques have arisen. Vibration energy harvesting has been focused by researchers due to the power generation capability and high power density of vibration. Energy is crucial for stimulating sensor nodes, Sensor networks, low-power electronics and traffic regulators. As a matter of fact, the number of research on energy harvesting from vibration has increased in the last decade. This paper presents a magnificent review on various energy harvesting techniques, energy harvesting sources, state-of-the art and various challenges of vibration energy harvesting. In the theory section various renewable energy sources, energy conversion and their introduction have been presented. In the third section various energy harvesting techniques for example mechanical vibrations, electromagnetic, piezoelectric and electrostatic have been discussed. Third section has explained various challenges of energy harvesting. In the conclusion, the author tried to explain the comparison among the harvesting techniques. Finally it can be said that, all of the things such as ambient renewable sources, energy harvesting techniques and facing challenges are crucial for new coming researchers in the energy harvesting field to solve the energy exigency from the society.

Index Terms— Techniques; Challenges; Energy Harvesting; Renewable Sources; Piezoelectric Materials;

1 Introduction

The current power generation activities from the form of fossil sources of energy are continually harming the planet. Portable electronic devices and wireless sensor nodes are typically powered by batteries. Because of the perpetual operation and limited power consumption, the sensor nodes and other low power electronics devices may experience power shortages and thus lead to many problems, including network disconnection and short range data acquisition. Replacement of batteries to power various nodes is not only costly but also difficult for inaccessible locations. To mitigate the problem associated with battery replacement and reduction of fossil fuel, renewable energy harvesting has come to the mind of researchers over the last few decades [1].

Renewable energy is the energy which is generated from various ambient sources for example solar, wind, tides, waves, and vibration. Improving the performance of solar cells is the concern of the energy industry as it provides an opportunity to reduce the cost of generating electricity from the solar. However, wind and piezoelectric materials are being used to scavenge sufficient energy for low powered devices. The cost of generating solar, wind and vibration energy is exceedingly determined by the efficiency of the capture and maintenance of the equipment. The most common way to harness solar energy is by converting it to electrical energy using photovoltaic (PV) modules. On the other hand wind energy and vibration energy can be produced by converting wind and vibrations of the environment. Among all the energy sources, vibration energy harvesting is more advantageous due to its high power density.

For scavenging electrical energy from vibration various techniques such as mechanical vibrations, electromagnetic, piezoelectric and electrostatic have become attractive to the researchers. Ambient energy harvesting from reliable and frequent mechanical vibrations can be found in indoor operating environments. Indoor machinery sensors may have ample amount of mechanical vibration energy that can be harvested and used reliably. Electromechanical or piezoelectric devices can be treated as vibration energy harvester. Currently electromechanical harvesting devices are most commonly researched and used devices.

Another technique for harvesting electrical energy using electromagnetic harvesting devices is a system of coils, springs and magnets where the coil and the magnet move relative to each other. According to Faraday's law of electromagnetic induction the movement creates a change in the magnetic flux which produces an electromagnetic force. Electromagnetic energy harvesters can generate electrical energy over a range of micro watt to kilowatt.

Like other techniques piezoelectricity is a technique which means that there is a coupling between the electrical and the mechanical state of the material. When a piece of piezoelectric material is mechanically deformed, e.g. compressed, a current will flow and charge its faces which is direct piezoelectric effect and vice versa, it will be deformed when exerted to an electrical field which is called inverse piezoelectric effect. Piezoelectric materials can be used to harness energy from vibration for robustness, reliability and low cost which is more beneficial for us. In this energy harvesting process, energy can be scavenged from vibration. With the help of contrastive exploration, the piezoelectric effect is widely employed because of its large piezoelectric coefficients and electromechanical coupling

factors as well as high energy circulation rates.
Electrostatic technique for scavenging electrical energy depends on the variable capacitance of vibration-dependent varactors. A variable capacitor is initially charged which will separate its plates by vibrations. In this way, mechanical energy is transformed into electrical energy. In electrostatic technique, a mechanical attraction force can be used to convert mechanical energy into electrical energy according to charged variable capacitor plates.
Energy scavenging from vibration can generate very small amounts of power. This limits its use to low-energy electronics such as:

- Powering sensor nodes
- Sensor networks
- Low-power electronics
- Traffic regulators

The contribution of vibration energy is increasing day by day tremendously for its high density of power to alleviate the power crisis of off-grid rural areas. The prominent trends of applying all of the mentioned techniques for harvesting vibration energy open up significant new business opportunities for the new researchers as well as for energy leaders. It is aimed that this paper will help the researcher to generate a large amount of renewable energy from vibrations which will be used to displace fossil fuels as both environmentally safe and economically sustainable.

1.1 Scope and Contribution

Now a days wireless sensors are being used in almost everywhere due to the advancement of low power electronics and Internet of Things. As a matter of low power consumption wireless sensor networks are used in every sector of human life such as military application, health monitoring, irrigation, fire detection and protection and switching electronics devices.
Though most of the sensor nodes are placed remotely, however these sensor nodes require their own energy source rather than battery because of their low longevity. Vibration energy source could be a reliable source to mitigate the energy crisis of sensor nodes in remote area. Vibration energy harvesting is a blessing for the society and new researchers. Firstly, human being will be benefitted using this vibration energy harvesting. Secondly, new researchers will be benefitted by getting ideas of various energy harvesting techniques from vibration source. Finally it can be said that this review paper will definitely be a pathway for new researchers to generate more energy for the society.

1.2 Formation of Paper

This review paper consists of various ambient energy sources found in the nature, different energy harvesting techniques and challenges of energy harvesting techniques. In section three various ambient energy harvesting sources have been discussed. In Section four Scavenged output power from different ambient sources.In section five different techniques such as mechanical vibrations technique, piezoelectric energy harvesting technique, electromagnetic energy harvesting technique and electrostatic techniques' is introduced. In section six various condition circuitry for different techniques have been discussed. In section various challenges have been discussed. Finally, in the lass section overall discussion has been made.

2 Background

A recent interest has been introduced in using micro and macro system to scavenge electrical energy from ambient vibration energy sources. Such micro and macro systems are mechanically modeled with the base excitation of an elastically mounted seismic mass moving particle. A foot wear system has been introduced to scavenge electrical energy using piezoelectric materials [2].Pressure variations has been converted into electricity using electrostatic and piezoelectric transducer because these transducer provides highest density of power over the electromagnetic transducer [3].

Due to the footsteps of a person who walks on the roof, the capacitance of electrostatic generator is increased and voltage is decreased. However, in the case of piezoelectric transducer voltage will be increased than the electrostatic generator as polymeric materials are used in both sides of piezoelectric material.

The efficiency of vibration based harvester depends on excitation frequency. The efficiency of vibration based harvester is proportional to excitation frequency. There was a proposal for a transducer which can convert vibration of lower frequency into a vibration of higher frequency by applying frequency up-conversion method [4].

For accomplishing this task a mechanical structure has been made consisting of a cantilever and a magnet attaching with a diaphragm which resonates at a frequency ranging from 1 Hz to 100 Hz. Due to the effect of external vibrations, at a certain time the magnet catches the movement of cantilever and pull them up. Then magnet releases the cantilever at another point at the same time cantilever starts to resonate at their natural frequency of high damped and in this way frequency of vibration is increased.

Due to the simple architecture, good scalability and high power density, piezoelectric transducer has been an ideal energy harvester from vibration for researchers in the last few decades [5].

In the last two decades, there has been a rapid development with an exponential growth in the field of portable electronic devices, including wireless electronics, mobile systems, sensors, microsystems and so-called "wearable electronics". Mobile phones represent a brilliant example of this new trend in the field of consumer electronics, while wireless sensors networks for control and monitoring are another example in the field of sensors. All these devices, regardless of their uses and purposes, need continuous and reliable electric power sources. Traditionally these types of devices were powered by electrochemical batteries, in various forms, shapes and dimensions, capable of providing a fixed amount of energy for a limited period of time. The use of batteries with limited charge lifetime results, however, in significant limitations in the life time of mobile and wireless devices, and produces the necessity of the recharge and/or the replacement, over time, of these batteries, which can be particularly problematic in the case of sensors operating in hazardous or inaccessible environments [6].

3 Ambient Sources

At the very beginning, the author briefly looks at energy harvesting ambient sources. All kinds of energy sources are crucial for energy harvesting. All in all, a thorough understanding of the target energy harvesting source is crucial in planning and building an efficient harvesting system. There are plenty of energy sources around the environment.

Among those ambient sources some are large scale and some are small scale energy sources in the environment. Among the ambient energy sources some are in the range of MACRO level on the other hand some are in the range of MICRO level [7]. Macro level sources for example solar, wind, geothermal, hydroelectric and nuclear sources are remarkable. Vibration, mechanical strain, fluid, water and human motion are said as Micro level sources. Micro scale energy sources are more suitable to power small scale electronics devices such as sensor nodes, portable electronic equipment and medical equipment for standalone operation. Energy harvesting is the way of converting ambient sources into electricity without wasting any amount of energy sources and the generated energy can be stored for further use. Truly ambient sources play a vital role for scavenging energy, especially high density sources that are more reliable for small autonomous devices, such as wireless sensor networks. A large diversity of sources is available for energy scavenging, including solar power, ocean waves, piezoelectricity, thermoelectricity, and mechanical vibrations. For instance, some systems convert random vibrations into useful electrical energy that can be used by wireless sensor nodes for standalone operation. Depending on the application, energy harvesting sources should be selected. According to the characteristics of ambient sources, a general overview of different sources is discussed in this section [8].

3.1 Mechanical Energy Source

Mechanical source is the renewable source of energy which can be found into the motion and position of an object. There are various mechanical sources in the environment which are converted into energy. Mechanical energy is the sum of kinetic energy and potential energy. Among all the mechanical sources, mechanical torment, promiscuous vibrations from machines, tension of high-pressure motors, industrial machines, and wasted rotations can be used as mechanical energy sources.

3.2 Mechanical Vibrations

Piezoelectric material vibrations and electromagnetics generator vibrations are the main mechanical vibration energy scavenging process. Using the mechanical rotation or vibration of piezoelectric patches piezoelectric energy can be scavenged. On the other hand, using the relative motion of magnet and coil electromagnetic vibration energy is harvested. A mechanical piezoelectric harvester is coupled with moving or vibrating objects, for example generators, vehicles, machines, and even human bodies. This is the efficient way of energy harvesting. To maximize the output voltage a conditioning circuit consisting of Schottky diode and MOSFET (IRf7853) is used. Using EH220-A4-503YB, piezoelectric vibration transducer (PVT) has been made commercially model EH220-A4-503YB.The process flow diagram has been given below.

energy of from the human body is transformed into electrical energy. There are various kinds of actions for example running, walking of human body and animal, battle of animals in fair could be used to scavenge large amount of electrical power.

3.7 Electromagnetic Energy

There are various forms of energy which are radiated, reflected or emitted from different objects in the form of magnetic or electrical waves whose are called electromagnetic energy. This type of waves is free to travel in the space. There are seven types of electromagnetic energy in space which are microwaves, infrared, ultraviolet, radio waves, optical, X-rays, and gamma-rays.

3.8 Radio Frequency

Radio Frequency energy scavenging is the method of generating energy from ambient RF sources. There are various range of radio frequencies including medium frequency of 526.5 to 1705 KHz for Amplitude Modulation, 87.5 to 108 MHz for Frequency Modulation, TV uses the frequency range of 470 to 700 MHz and Wi-Fi usage 2.4 to 5GHz Radio Frequency energy does not depend on environmental conditions for example temperature, pressure, weather and climate [13].

In our daily life huge amounts of electromagnetic waves are radiating from various sources for example tower, Bluetooth, radio transmission tower and routers. These electromagnetic waves are then converted into electrical energy for various electronics devices. For efficient communication or transmission of signals, a transmitter needs to send signal in omnidirectional way. As a result many waves are wasted due to receiver directivity. This unused electromagnetics wave then be converted into electrical energy.

3.9 Optical Energy

The incident light form the sun is collected, concentrated, coupled, transformed and absorbed by the optical elements and then converted into electrical energy in solar system. To generate electrical energy a luminescent solar concentrator (LSC) is used for concentrating radiation in this case solar radiation in particular. This energy is mainly harvested in outdoors which can be classified into four groups based on two characteristics such as controllability and predictability. Controllability means an energy harvesting system may or may not have full or partial control over its energy harvesting sources. On the other hand the degree to which the ambient sources are predicted and modeled is called predictability.

4 Energy Harvesting Techniques

Harvesting energy is a crucial thing for the researchers since a long time. Researchers have been adopting various methods to exploit energy from different ambient vibration source. Usual resolution for vibration energy to electrical energy conversion is mostly achieved using various techniques such as electromagnetic, electrostatic, mechanical vibration and piezoelectric methods. All methods are being used separately to scavenge energy from ambient sources. Two or more of these techniques are sometimes combined together to enhance performance of the mechanical harvester. For investigating all of the above energy harvesting techniques various models for example finite model, analytical model, block diagram, flow diagram and their equivalent circuit have been described in this section.

To explore the energy harvesting capability of each approach, various models have been constructed in last few decays including analytical models, finite element models, and equivalent circuit models. Regardless of which technique was employed, the majority of past research concentrated on creating a linear vibration resonator that achieves maximum system performance at its resonant frequency. The harvester's performance can be drastically reduced if the stimulation frequency is slightly shifted. Because the bulk of practical vibration sources exist in frequency varying or random patterns, expanding the bandwidth of vibration energy harvesters is one of the most difficult difficulties to solve before they can be used in practice.

In the railway sector, several electronic equipment’s are employed. Each one necessitates a different amount of electrical energy, ranging from low power (such as μW for health monitoring sensors) to moderate/high power devices (W for signaling lights, for example). There is a significant quantity of vibration and sound energy available in the railway industry to provide the requisite mechanical energy for energy harvesting.

4.1 Mechanical Vibrations

In order to harvest electrical energy from an ambient vibration source, an indoor operating environment could be an efficient place for providing constant mechanical vibration source. Ample amount of mechanical vibration can be found from indoor machinery sensors which can be converted reliably. In mechanical vibrations energy harvesting technique, mechanical excitement is generated by vibrations which cause the movement and oscillation of mass component. Due to the opposition of frictional and damping forces applied against the mass, there is an extinguishment of oscillations. The produced damping force then can be converted into electrical energy with the help of some methods for example magnetic field, strain and electric field. Vibration energy can be harvested from the handrail subway, human running, bridge and external transmitter. There are various applications of mechanical vibration energy for example the generated electrical energy from mechanical vibration can be used for IoT devices, electronic devices, wireless sensor networks etc.

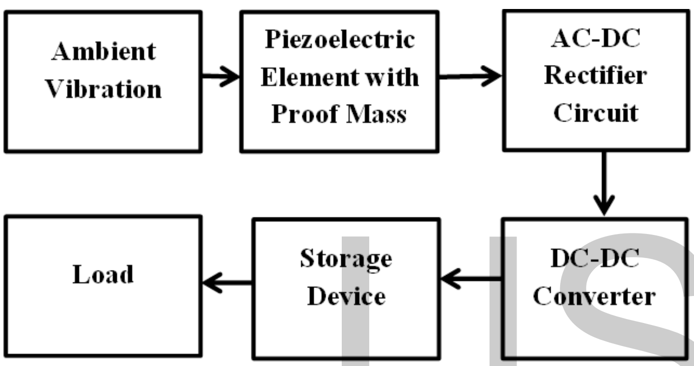

Fig 4: Block diagram of mechanical vibration energy harvesting

4.2 Electromagnetic

Among all the energy harvesting techniques, electromagnetic technique is the best way to convert mechanical energy to electrical energy using magnetic fields. A magnetic coil is coupled with the oscillating mass for passing through a magnetic field. The magnetic field is generated by an artificial magnet to produce electrical energy. The induced voltage is inherently small and therefore must be increased to become a viable source of energy. Techniques to increase the induced voltage include using a transformer, increasing the number of turns of the coil, or increasing the permanent magnetic field. In various transportation fields such as speed-bump and vehicle suspension, electromagnetic technique for energy harvesting from vibration has been thought and prototyped. Electromagnetic energy harvesting technique has been used to scavenge electrical energy owing to its better harvesting efficiency and good controllability. Rotary and linear generators are used in electromagnetic based vibration energy scavenging technique. Linear generators are very simple to implement on board and on the track side due to the simple structure and mechanism. On the other hand rotary generators use mechanical vibration rectifier which convert linear vibration into rotational motion. The rotary electromagnetic VEH generators have complex structure, higher energy density and can be more compact. However, linear generators are simple. In railway transmission system, electromagnetic energy scavenging technique is most attractive way of energy harvesting from vibration. In this system the kinetic energy of vibration is converted into electricity using coils. Generated electrical energy in railway system can mitigate the energy crisis of monitoring sensors of rail [14].

Permanent magnet and coils are used in electromagnetic linear generators. The produced vibration from train can be used to drive the relative movement between the coil permanent magnet. As a result, the current is generated in the coil due to the relative movement of coil and magnet. The rotary electromagnetic harvester converts vibration into rotation of the shaft at first and then moves the harvester to scavenge electrical energy [15].

According to the law of electromagnetic induction, the produced electromotive force between electromotive force and magnetic flux can be written as follows:

$$\mathrm{V} = -N\frac{\mathrm{d}\emptyset\mathrm{B}}{dt} \dots \dots . \dots (1)$$

From equation one it can be seen that, v is the induced emf, N is the number of turns and ΦB is the magnetic flux.

The relative motion in a linear generator can be achieved in one of two ways: (1) the coil or magnet is attached to a vibratory element, as shown in Fig. 7.a, or (2) the magnet is suspended by a spring and the generator's base is mounted to a vibratory element, as shown in Fig. 7.b [16]. To achieve maximum output with the second design, frequency adjustment between the natural frequency of the generator and the dominant frequency of vibrations is required.

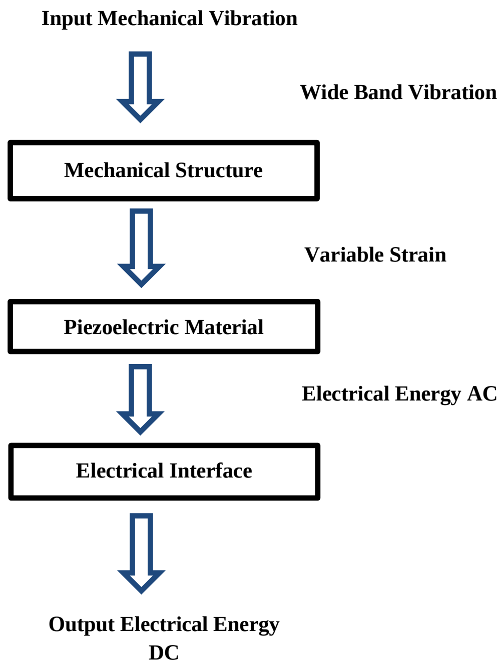

Fig .7. Process flow diagram of energy harvesting from vibrations.

A mechanical device consisting of two piezoelectric materials, a cantilever beam, a proof mass and clamper in both ends have been developed to develop an energy harvesting system for low cost power management. Placement of mechanical device has been implemented in agriculture and forestry where we need energy to establish wireless sensor networks to power sensor nodes. Conditioning circuit has been implemented for proper energy harvesting and energy storage for wireless sensor nodes. The vibrations need to have a steady vibration and a controlling frequency when the intent is to power a sensor or monitoring system. It has been assured to provide steady vibrations as source to energy harvester. Then the research has been conducted under any circumstances and evaluating the performance of the mechanical device. Dynamical characteristics have been found from mechanical device by walking and shaking in various frequencies [17].

4.4 Electrostatic Technique (Capacitive)

Electrostatic is a micro-scale energy harvesting technology that scavenges electrical energy from mechanical vibrations. They produce charges from relative motion between two plates using a variable capacitor construction. With the use of silicon micro technologies, capacitive energy harvesters are utilized to gather energy. A variable capacitor can be utilized in pre-charged mode to transform mechanical vibration into electrical energy due to the passive nature of capacitive transducers. This energy harvesting technique employs a vibration-dependent varactor. The action of vibrations separates the plates of a primary charged variable capacitor, converting mechanical vibration into electrical energy. The conversion is accomplished using two different mechanisms: constant voltage or constant current.

The voltage across a variable capacitor is kept constant when its capacitance changes after a primary charge. As a result, the plates break and the capacitance decreases until the charge are discharged. The generated energy can subsequently be stored in an energy pool or utilized to charge a battery, providing the required voltage source. Given that MEMS (Micro-electromechanical system) variable capacitors are produced using very well-known silicon micro-machining processes, the method's most noticeable feature is its IC-compatibility.

Electrostatic converters are capacitive structures that consist of two plates separated by air, vacuum, or any other dielectric medium. A change in capacitance and subsequent electric charges is caused by relative movement between the two plates. These gadgets can be classified into two groups:

Electrostatic converters with no electrets that use conversion cycles made up of capacitor charges and discharges (an active electronic circuit is then required to apply the charge cycle on the structure and must be synchronized with the capacitance variation).

Electret-based electrostatic converters are electrostatic converters that employ electrets to transform mechanical energy directly into electricity.

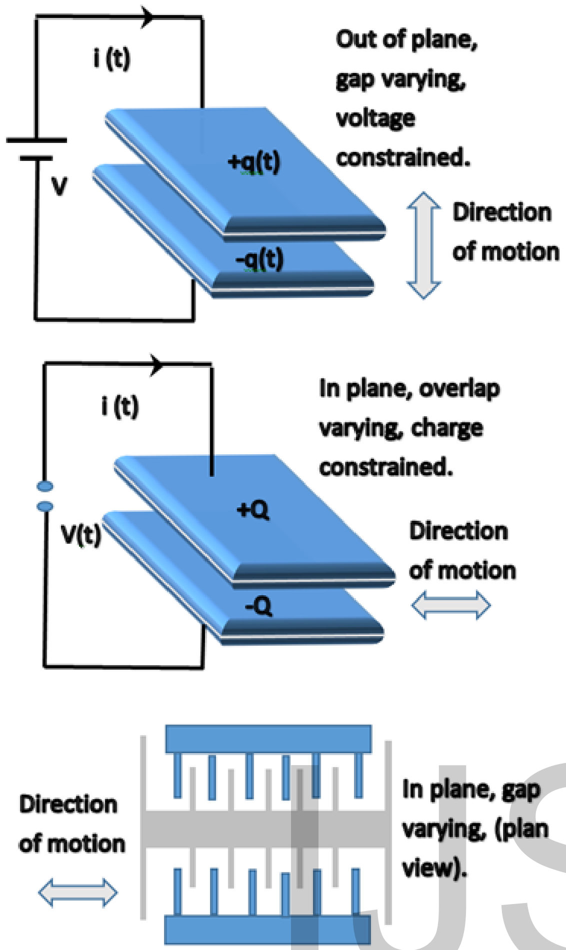

Fig. 8. Types of electrostatic energy harvesters [18].

Among the energy collecting systems, the electrostatic principle is the most basic. It is based on the relative motion between the two plates of a charged capacitor, which acts as a variable capacitor (C_v) and contains the same electric charge (Q). As a result, there will be a change in the electric potential (V) across the capacitor (Q = CV). Different types of electrostatic energy harvester designs are shown in Fig. 6. The key advantage of this sort of energy harvester is its compatibility with application microchips, such as sensors, to act as their power source and supply them with electrical power whenever energy harvesting happens.

4.5 Tribo-electric methods and nanogenerators (TENGs)

Triboelectric nanogenerators transform mechanical energy from the environment into electricity, which can be used to operate small devices like sensors or recharge consumer gadgets. TENGs have several advantages, including their minimal weight, ease of manufacture, and low cost. The energy conversion efficiency from mechanical to electrical is roughly 70%. On the contrary to Piezoelectric and electromagnetic methods, tribo-electric methods works well in low frequencies (lower than 10 Hz), which are dominant frequency ranges in railway industry. The method is able to convert a wide range of motions to electricity for example rotary motions, body motions, wind/wave motions, etc. Tribo-electric effect is based on the electrostatic energy conversion.

When two materials come into touch with each other, they become electrically charged. "Relative polarity of a material" is defined here as an important parameter. Tribo-electrification occurs in almost all materials. This characteristic determines a material's ability to gain or lose electrons. After tribo-electrification, relative polarity determines whether a material is charged positively or negatively. Surface properties of the two tribo-electric materials, in addition to material composition, have a substantial impact on tribo-electrification charge [19].

5 Comparison of Energy Harvesting Sources

According to the description of all ambient sources, each source possesses some advantages and disadvantages. For example, using mechanical vibrations of different frequencies a good amount of power can be scavenged in mW range compared to constant frequency. Solar energy in an outdoor situation has the highest power density with hundreds of mW of power output, but is only available in the daytime. Wind can generate power in mW range using high temporal variations of wind. RF energy is available continuously (day and night). RF energy in the AM band has the longest energy harvesting distance among all RF energy sources without the limitation of line-of-sight propagation conditions. A table of various ambient sources with their efficiency, characteristics, output power and applications which is shown in table 1.

Table 1: Scavenged output power and efficiency of various ambient sources with their applications

Energy Source	Characteristic	Efficiency	Scavenged Power	Applications
Solar (Outdoors)	Clean with high absorption layer and sun tracker	6%-35%	1350mW	AC & DC Load
Solar (Indoors)	Inexhaustible, Clean with internal lighting	3%-7%	621µW	Small scale electronics devices
Wind	High temporal variations	7%-20%	0.77mW-439mW	National electrical grids and providing electricity to rural residences or grid-isolated locations.
Mechanical (vibration from machine)	Non linear frequency	20%-40%	200µW-40mW	Handheld Electronic Devices or Remote Wireless Actuators bearable electronics devices
Mechanical (vibration from human motion)	Linear and Non-linear frequency	10%-30%	0.84mW-4.13mW	Small scale electronics devices
Radio Frequency GSM 900	Longest wavelengths with smallest frequency	5%-15%	1mW	Remote Wireless Sensors
Optical Light	Luminescent solar concentrator	6%-10%	100mW/cm2	Handheld Electronic Devices

6 Challenges

Harvesting energy for low-power devices like wireless sensors provides a unique problem because the energy harvesting device must be comparable in size to the sensors. At the time of designing energy harvesting circuits for WSNs, complicated tradeoffs must be considered due to the interaction of numerous elements such as the behavior of the energy sources, the energy storage device(s) employed the power management capabilities of the nodes, and the applications' requirements. Solar, mechanical vibration and thermal energy are the main sources of ambient energy currently deemed acceptable for use with wireless sensor networks. Finally, the paper discusses the obstacles and issues that have yet to be fully addressed in the present research literature, such as system stability, durability, and cost. For further examination, several recommendations are made to fill these research gaps. Because it eliminates the need to replace batteries, small size electronics devices powered by ambient energy harvesting are a promising technique for many sensing applications. However, the current state of energy collecting technology is unable to offer a constant energy source to allow sensor nodes. The main disadvantage of linear resonating harvesters, namely their narrow bandwidth, restricts their use in actual applications where ambient vibration is present. The source is either random or frequency-variant. Furthermore, the ability to collect energy from the environment is highly dependent on a number of environmental conditions, which will require additional research to fully comprehend and use. We've given you a high-level summary of the research in the field of ambient energy gathering. Some challenges are given below.

6.1 Bandwidth

The majority of vibrational energy harvesters are intended to operate in resonance mode, with a modest half-power bandwidth. Because the frequency of ambient vibrations varies widely, from 1 Hz for heel tapping to 240 Hz for an electric tea pot, this is one of the most difficult issues of energy harvesting. Some vibration sources, such as industrial machinery, can provide consistent frequency vibrations for lengthy periods of time. A synchronous AC electric motor running in a factory during working hours, for example, would produce vibrations at the AC line frequency for 8 hours every day. However, due to frequency shifts in the vibration source or drifts in the resonance frequency, even harvesters employing this sort of source may require adjusting. This problem is exacerbated by random ambient vibration sources, which can cover a wider frequency range. In this instance, it would be impossible to continuously measure the vibration and manually tune the harvester's resonance frequency. Dynamic resonance frequency tuning and broad bandwidth harvesters are two possible solutions to this challenge. Several study groups have looked into both methods in the literature.

6.2 CMOS compatibility

Monolithic sensors and transducers can be made using CMOS compatible MEMS technologies, in which the mechanical and electrical portions are fabricated on the same substrate. The entire device size and cost are reduced because to monolithic construction. Furthermore, rather than wire bonding, micro processing is used to finish the interconnections between the mechanical and electrical sections, which improves dependability and decreases parasitic effects. The development of a CMOS compatible technique that does not destroy the electrical circuitry while creating the mechanical pieces is essential for a monolithic device.

Thin-film PZT, which is typically created using the sol-gel process, is the most prevalent material used in MEMS scale PEHs. PZT crystallization occurs at roughly 600–700 degrees Celsius, hence the coated films must be annealed at these temperatures to achieve piezoelectric properties. Although additional methods for depositing thin films of PZT exist, such as aerosol deposition or epitaxial growth, all of these approaches necessitate a high temperature for good crystallization. As a result, these devices are CMOS incompatible.

Bulk PZT has a thickness of around 200 lm, which is too thick for a MEMS device; as a result, the bulk PZT crystal is mechanically thinned after bonding. As a result, the suggested method achieves CMOS compatibility at the expense of higher fabrication complexity. Sputter deposition can be used to grow c-axis oriented piezoelectric materials like ZnO and AlN. In most cases, the requisite temperatures are minimal, and no subsequent poling is required.

6.3 Biocompatibility

IMDs are one of the most promising uses of PEHs. According to the literature, there has been a lot of effort put into building self-sustaining IMDs employing PEHs. The biocompatibility of the materials used in IMDs is one of the most critical factors. Because of its poisonous lead level, the most often used piezoelectric material, PZT, is not suitable for implants. Potassium sodium niobate (KNN), a lead-free piezoelectric material with similar piezoelectric characteristics to PZT, is an alternative.

7 Conclusion

For WSN nodes, embedded systems, and wearable electronic devices that are located remotely, harvesting energy from the surrounding environment is the ideal solution. There are various alternative energy sources that can be employed for this purpose, as they are currently underutilized. However, the solution should take into account the application's requirements as well as the context in which it is used. Despite the fact that many efforts are being made to provide alternative energy sources for WSN, embedded systems, and wearable electronics, it is quickly gaining traction in the research community, driven by the ever-increasing demand for small and efficient power sources for sensors nodes, embedded systems, and wearable electronic devices.

This study looked into energy scavenging as a means of generating electricity. Solar cells, thermoelectric generators, mechanical, and electromagnetic energy scavenging sources were all discussed. Researchers interested in energy scavenging will find useful references, which will aid in the development of future directions in "long-term energy sources" study. Many possible technologies, as well as many new modes of exploration, might be envisioned based on the research lines mentioned in this paper. For most applications, combining energy scavenging from many sources can be an effective solution. In this area, some initiatives have already begun.

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