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MECHANICAL ENERGY HARVESTING DEVICES FOR LOW FREQUENCY APPLICATIONS: REVISITED

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ABSTRACT

With the advancement in low power system technology, energy harvesting systems have become a research hotspot over the last decade. The main advantage of the system is that they require minimum maintenance which makes them to be deployed in large scale or previously inaccessible locations. Therefore, the target of energy harvesting is to power autonomous electronic systems over their lifetime. Mechanical energy is the most ubiquitous and accessible energy source in the surroundings. Harvesting this type of energy exhibits a great potential for remote wireless sensing devices, charging batteries, and powering electronic devices. In this paper, we reviewed self-powered, self-sensing devices which describe different ways of mechanical energy harvesting. Comparison of mechanical energy harvesting devices in terms of their power output and frequency were presented. Self-powered system offers great potential for solving difficult problem of supplying energy.

Keywords: devices, energy harvesting, vibration.

INTRODUCTION

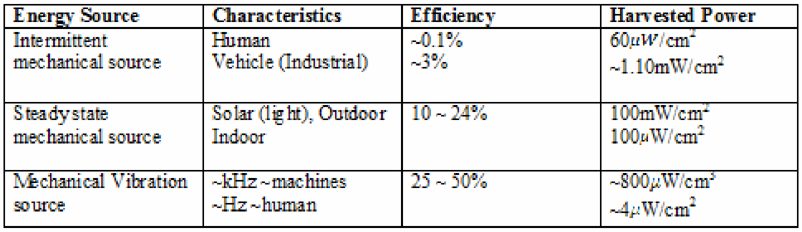
Energy harvesting can be obtained from different energy sources, such as mechanical vibrations, electromagnetic, light, wind and temperature variations. It converts ambient energy into usable electrical energy. When compared with energy stored in common storage device, such as batteries, capacitors, and super capacitors, it has more advantage of sustainability. Systems continue to become smaller, yet less energy is available on board, leading to a short run-time for a device or battery life. High energy density batteries have been design but the amount of energy available in the batteries is not only finite but also low, which limits the life time of the systems.

Extended life of electronic devices is very important; it also has more advantages in systems with limited accessibility, such as those used in monitoring a machine or an instrument in a manufacturing plant used to organize a chemical process in a hazardous environment. The critical long-term solution should therefore be independent of the limited energy available during the functioning or operating of such devices. Mechanical Energy Harvesting Systems may enable wireless and portable electronic devices to be completely self-sustaining.

Mechanical energy sources

Mechanical energy harvesting sources can be classified as follows. Intermittent mechanical source: human activities and Vehicle passing. Mechanical and thermal energy can be generated from human or animal activities such as walking and running. Steady state mechanical source: Wind, water flow, ocean waves, and solar energy can provide limitless energy availability from the environment. Mechanical vibration source: from machines, mechanical stress, and strain from high-pressure motors, manufacturing machines, and waste rotations can be captured and used as ambient mechanical energy sources. Table-1 shows the classification of mechanical energy harvesting sources.

Table-1. Sources of mechanical energy harvesting.



Energy Source	Characteristics	Efficiency	Harvested Power
Intermittent mechanical source	Human Vehicle (Industrial)	~0.1% ~3%	$60\mu W/cm^2$ $\sim 1.10 mW/cm^2$
Steady state mechanical source	Solar (light), Outdoor Indoor	10 ~ 24%	$100 mW/cm^2$ $100 \mu W/cm^2$
Mechanical Vibration source	~kHz ~ machines ~Hz ~ human	25 ~ 50%	$\sim 800 \mu W/cm^3$ $\sim 4 \mu W/cm^2$

Mechanical (vibration) energy harvesting systems

The ability of an energy harvesting device to produce power depends on both the available energy and on the efficiency to which that energy can be converted to useable electrical energy.

A system was designed to capture rotational movements by the help of the mouse ball to generate and harvest electric power (Mikami *et al*., 2005); the electric generator is powered through exploiting rolling energy by dragging the mouse. The energy-harvesting system was intended to power the electronic system of a mouse device, such as the ultra low power RF transmitter and microcontroller. The total energy captured using an energy-harvesting system was higher than 3mW, which was enough for the wireless mouse operations in a transmit range of one meter.

A novel wireless sensor system that harvests vibrations of the bridge created by passing traffic which is converted into usable electrical energy by means of a linear electromagnetic generator, allows harvesting of up to 12.5mW of power in the resonant mode with the frequency of excitation at 3.1Hz (Edward *et al*., 2009). Because of the high level tight integration of the power generator and a smart algorithm for energy conversion that switches between the low-power mode and the impedance matching mode, the device performance was good and should be encouraged for improvement. Busy roads, railway track beds and runways the airport, has the potential to convert into electrical energy Figure-1. As the car moves along the road, the vertical displacement takes place under the tires, which transmit the weight of the vehicle on the road and the reaction will result to heat. With piezoelectric generators embedded in road materials, part of the energy expended on deformation of the road can be converted into electrical energy (piezo-electric effect).

Figure-1. A novel battery-less wireless sensor embedded in the road.

Another mechanical energy harvesting base on electrostatic micro generator was proposed by (Sterken *et al*., 2003). In this system, a micro electrostatic converter Figure-2, consisted of a vibration sensitive variable capacitor was polarized by an electret. A general multi domain model was built and analyzed in the same study, and it showed that power generation capabilities up to 50µw for 0.1cm^2 surface areas were attainable and used. The output power is very low to be use for powering portable devices. If the charge on the capacitor is maintained constant while the capacitance decreases the voltage will increase. If the voltage on the capacitor is maintained constant while the capacitance decreases, the charge will decrease. The mechanical energy converted into electrical energy is greater if the voltage across the capacitor is constrained than if the charge across the capacitor is constrained. However, the initial voltage source needed has a smaller value if the charge across the capacitor is constrained. A way to increase the electrical energy for the charge constrained method is add a capacitor in parallel with the MEMS capacitor. The main disadvantage of this method is that a separated voltage source is needed in order to place an initial charge on the capacitor plates.

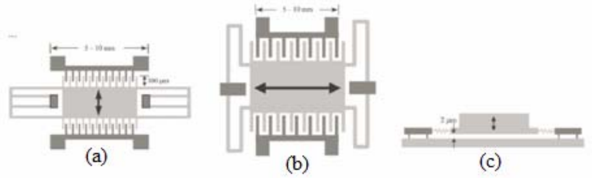


Figure-2. Three possible topologies for micro electrostatic converters (Sterken *et al*., 2003).

Dynamic models with electromechanical couplings have been established (Yu-Jen *et al*., 2012), with output power of approximately 300-550mWatt at about 200-500rpm. The magnets were integrated in a novel circular Halbach array and coils into the design to augment the magnetic strength on one side of the array where the coils are placed. Because the magnetic flux density for the circular Halbach array disk is larger than that of the multipolar magnetic disk, it utilizes the presence of the nonlinearity model and the well-weighted swing disk to maximize the power output and the frequency bandwidth for a wheel rotating at any speed. The Circular Halbach array magnetic disk and multipolar magnetic disk are shown in Figure-3.

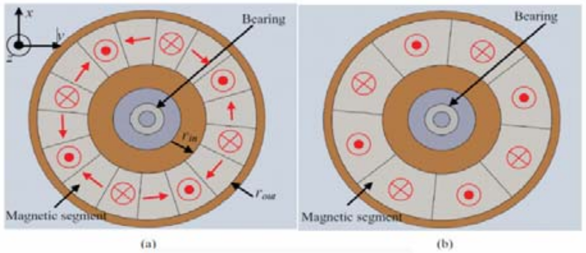


Figure-3. Schematic diagrams of (a) Circular Halbach array magnetic disk, (b) multipolar magnetic disk (Yu-Jen *et al*., 2012).

Researchers have developed various electromagnetic vibration energy harvesters ranging from micro electro mechanical (MEM) devices (Shearwood and Yates, 1997) to larger system (Glynne-Jones *et al*., 2004). (Roundy *et al*., 2004) Develop a system that produced energy from vibrations which is based on the movement of a spring-mounted mass relative to its support frame. Mechanical acceleration is produced by vibrations that, in turn, cause the mass component to move and oscillate. This relative displacement causes opposing frictional and damping forces to be applied against the mass, thereby reducing and eventually extinguishing the oscillations. The damping force energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material.

In electromagnetic energy harvesters, permanent magnets are normally used to produce strong magnetic field and coils are used as the conductor. Either the permanent magnet or the coil is fixed to the frame while the other is attached to the inertial mass. In most cases, the coil is fixed while the magnet is mobile as the coil is fragile compared to the magnet and static coil can increase lifetime of the device. Ambient vibration results in the relative displacement between the magnet and the coil, which generates electrical energy. According to Faraday's Law, the induced voltage, also known as electromotive force (e.m.f), is proportional to the strength of the magnetic field, the velocity of the relative motion and the number of turns of the coil. Generally, there are two types of magnetic induction system as shown in Figure-4. Electromagnetic device (magnet/coil) configurations have been considered in research and a limited number of commercial units were developed (www.perpetuum.co.uk, 2008) the device is capable of converting up to 30% of the total energy supplied into useful electrical energy.

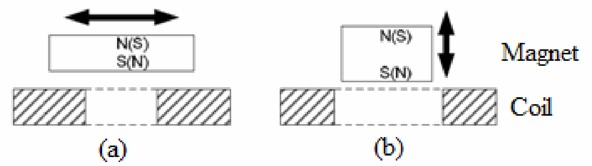


Figure-4. Movement of magnet: (a) across and (b) through a coil.

Demonstration of a vibration driven electromagnetic energy harvester for a self-powered system was presented by (Byung *et al*., 2012). The energy harvester consists of NdFeB permanent magnets, a planar spring, and a cylindrical-type copper coil. The released device generated a maximum output power of 1.52mW against a load resistance of 5.46 kΩ at a resonance frequency of 16Hz. Compared to the previously design reported low frequency driven energy harvesters, this prototype can generate higher output power at lower frequency. A self-powered device driven by nanogenerator (Xiaohong *et al*., 2012) was designed. Device showed desirable output of 140W and the sputtering time was 30 minutes. The sputtering target was tungsten oxide and the purity 99.99%. The thickness of the film as measured by a profilometer was about 250 nm. The device can be use not only for monochrome displays or electronic billboards but also for portable electronic devices.

A generator consisting of a permanent magnet core mounted at the tip of a planar steel beam. As the device is shaken, the resonant beam oscillates back and forth. The results show an output power of 0.53mW with an input vibration of amplitude 25µm, and frequency 322Hz. excluding the clamp at the base of the beam and the coil mounting, the device requires a volume of 0.24cm^3. It is interesting to note that, regarding the small size of this device, micromachining techniques were not used in its construction (El-hami *et al*., 2000). An important point to be considered in practical energy harvesting systems is the possibility of having a fully self powered circuitry. In other words, the energy harvested by the transducer and stored in a capacitor, in a super capacitor or in a rechargeable battery should also supply the active circuitry. (Enrico *et al*., 2011) design an active electronic interface for an energy harvesting system including a vibration based electromagnetic transducer. The transducer provides a peak voltage of 3.25V when operated close to its mechanical resonance frequency about 10.4 Hz. The circuit is a full-cycle inductive step-up ac/dc converter able to process every voltage pulse coming from the transducer. From the result it makes the system fully autonomous.

A micro machined generator that comprises a permanent magnet mounted on a laser-micro device spring structure next to a coil, occupying around 1cm^3 generates 10µW of power at 2V DC with an input excitation frequency of 64Hz and amplitude of 100µm (Li *et al*., 2000). With the generated high frequency of the machine, it can be used for devices that require very low power and high frequency. A new micro electromechanical systems (MEMS) self-powered sensor and RF transmission platform for wireless sensor network (WSN) nodes has been design to operate at energy levels. This device drive a passive kick-and-resonate transmitter architecture as an alternative to a standard power hungry transmitter, this platform eliminates the need for both secondary energy storage and power conditioning circuits (Cairan *et al*., 2011). It may be highly impractical to regularly replace or recharge embedded or implanted batteries, especially if there are many nodes forming a network. Much research effort in recent years has been devoted to the promising alternative of harvesting ambient energy as a potentially inexhaustible source of power for wireless sensor nodes.

A novel technique for generating power from vibrations is developed which consists of a thick- film piezoelectric layer deposited on to a thin steel beam. As the beam is shaken and begins to resonate, the piezoelectric material is deformed and generates electrical energy. Initial results show that the prototype can generate up to 3µW of power at 90Hz (Gynne-Jone *et al*., 2000). However, order of magnitude improvements are shown to be possible by varying the material systems. More research needs to be done on this type of device so that a detailed studies. A new low-cost self-powered supply for bidirectional insulated-gate bipolar transistor switch gate drivers was presented by (Nabil *et al*., 2012). The proposed circuit allows the gate driver power supply of the bidirectional switch without using a transformer or any external added dc supply. There are also drawbacks associated with this design, more switching devices and associated gate driver circuit power supplies and protection systems are required.

A system was design which converts mechanical energy into electrical energy by straining a piezoelectric material (Sodano *et al*., 2004). Deformation of a piezoelectric material causes charge separation across the system, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, this provide higher strain for a given input force. The voltage produced varies with time and strain, effectively producing an irregular AC signal on the average. In many energy harvesting applications, the output of the device which converts the mechanical excitation into an electrical phenomena (voltage or current) is connected to a rectifier comprised of diodes. A self-powered rectifier was design for low-frequency (20Hz) energy harvesting applications in embedded structural health monitoring (SHM) of bridges where the output voltage from the energy harvester is less than 1V (Jason and Aydin 2011), the low voltage comparator is solely powered by the generated dc output of the rectification circuitry, thus eliminating the need for an external battery whose lifetime is typically less than that of the structure being monitored. In other to overcome the low input amplitudes, gate drive to the switches should be provided to help reduce their ON resistance and speed up the comparison process which aides in the overall rectification.

Piezoelectric energy conversion produces higher voltage and power density levels than the electromagnetic system. Moreover, piezoelectricity has the ability of some elements, such as crystals and some types of ceramics, which generate an electric energy from a mechanical stress (Skoog *et al*., 2006); this process takes the form of separation of electric charge within a crystal lattice. If the piezoelectric material is not short circuited, the applied mechanical stress induces a voltage across the material. Applications based on piezoelectric materials are many, one of which is the electric cigarette lighter, by pushing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the voltage that is produced injects the gas slowly as the current jumps across a small spark gap. Following the same idea, portable sparkers used to light gas grills, gas stoves, and a variety of gas burners have built-in piezoelectric based ignition systems and Electrostatic (Meninger *et al*., 2001) and (Despesse *et al*., 2005).

Using piezoelectric materials to convert mechanical energy into electrical energy for batteries of wireless devices in order to extend the lifetime is the focus in many researches in the recent years. A self-powered piezoelectric energy harvesting device was design based on the velocity control synchronized switching harvesting on inductor technique (Chen *et al*., 2012), most piezoelectric electricity sources produce power on the order of milliwatts, too small for system application, but they have the ability to transform mechanical strain energy into electrical charge. Some of them, the excitation level does not influence the performance of the system which is better than the performance of the conventional device which requires an excitation level high enough to work properly (Liang and Liao, 2009).

A variable capacitor, which is initially charged, will separate its plates by vibrations; in this way, mechanical energy is transformed into electrical energy. Constant voltage achieves the conversion through two different mechanisms. For example, the voltage across a variable capacitor is kept constant as its capacitance alters after an initial charge. As a result, the plates split and the capacitance is reduced, until the charge is driven out of the device. The driven energy then can be stored in an energy pool or used to charge a battery, generating the needed voltage source. This produces higher and more practical output voltage levels than the electro- magnetic method, with moderate power density. A research conducted to test the feasibility and reliability of the different ambient energy sources by (Marzencki, 2005) three different vibration energy sources (electrostatic, electromagnetic, and piezoelectric) were investigated and compared according to their complexity, energy density and size. These three has demonstrated a good potential for energy harvesting. Though, there shortcomings differs from one another.

A self-powered computer protection device based on the 16-bit microcontroller was design by (Liu *et al*., 2011). The device is suitable for switching station and power distribution. It coordinated with circuit breaker to completely replace protected mode of fuse with a full load isolation switch, and can significantly increase the load protection of the distribution network. This is an improvement to the system relay protection device.

Intermittent mechanical energy harvesting systems

Sources of ambient mechanical energy which are intermittent include energy available from vehicles passing over an energy harvesting device which generate heat and convert it to electrical energy and human activities such as walking or running. Thermoelectric generator consists of a thermocouple, comprising a p-type and n-type semiconductor connected electrically in series and thermally in parallel as shown in Figure-5. The thermo generator produces an electrical current proportional to the temperature gradient between the hot and cold junctions. An electric load is connected electrically in series with the thermo generator creating an electric circuit. The coefficient is positive for p-type materials and negative for n-type materials. The heat that enters or leaves a junction of a thermoelectric device has two reasons: (1) the presence of a temperature gradient at the junction. (2) The absorption or liberation of energy.

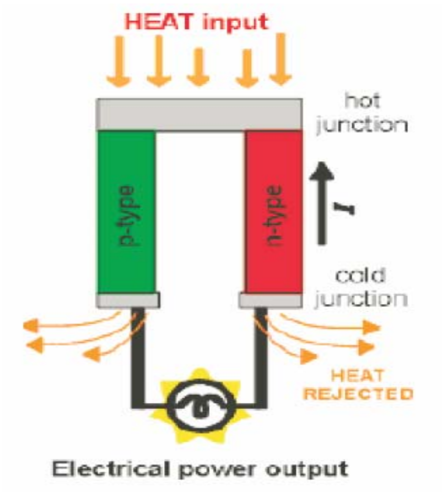


Figure-5. Thermoelectric generator (Loreto, 2004).

Generated voltage and power is relative to the temperature differential and the coefficient of thermoelectric materials. Large thermal gradients are essential to produce practical voltage and power levels (Roundy *et al*., 2003). Thermoelectric contain no materials that must be replenished, heating and cooling can be reversed but one downside to thermoelectric energy conversion is low efficiency (currently less than 10%).

However, temperature differences greater than 10°C are rare in a micro system, so consequently such systems generate low voltage and power levels. Moreover, naturally occurring temperature variations in an environment, can provide a means by which energy can be scavenged from the surroundings with high temperature.

A passive network, built from low threshold-voltage chip diodes and capacitors, generates a dual supply voltage from one of the coils to power up the active rectifier was design by (Arian *et al*., 2012), The system delivers 54 μW to a 37-μA load through a dual rail 1.46 V DC voltage with total system efficiency of 81%, when subjected to low frequency of 8 Hz external vibrations. The maximum overall system power density has been validated to be 6.06 μW/cm^3. Performance has given an output three times what was previously reported for a battery less vibration driven system. Arrays of multiple thermocouples may be used in order to increase the voltage and power level (www.poweredbythermolife.com) design a device which produce 100 μW from a specific temperature difference in a 9.3mm diameter device 1.4mm thick. In this system the voltage and power associated with each individual thermocouple is very low.

One of the latest designs of thermoelectric energy harvester is the thermoelectric generator designed and introduced by (Pacific Northwest National Laboratory, 2009) this new thermoelectric generator is used to convert environmental (ambient) thermal energy into electric power for a variety of applications that necessitates low power use. Depending on the temperature range, the thermoelectric generator output can be changed from a few microwatts to hundreds of mill watts and more by modifying the design. Applications of this energy harvesting design are diverse, including automotive performance monitoring, homeland and military security surveillance and agricultural management. Power may be recovered passively from body heat, breathing, blood pressure, arm motion, typing and walking. A summary of the potential power sources and the total power from various body-centered actions is provided in Figure-6. (Harkanwal and Choudhary, 2012) Presented a health monitoring system utilizing energy scavenging from body movements for signal transmission through wireless antenna. The device converts mechanical energy produced by body movements to electrical energy. This system can further be enhanced by incorporating the design in other wearable materials to harness energy from various body movements.

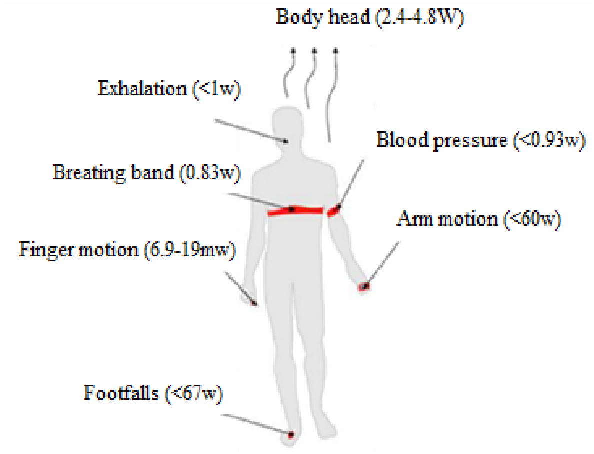
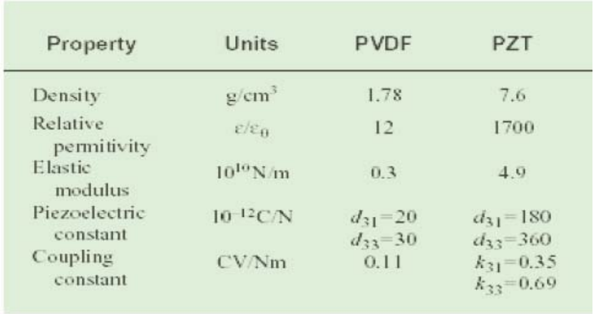


Figure-6. Potential human power sources. (Starner, 1996).

Walking is one of the usual human activities that can be use to harvest energy (Kymissis *et al*., 1998). He analyzes power generation from breathing, body heat, blood transport, arm motion, typing, and walking.

Piezoelectric materials, dielectric elastomers and rotator generators have been employed in order to harvest energy from human walking activity by some laboratories. In general, energy harvesting from human activity can be classify as active or passive. Active power means that the user is doing a specific work to generate the energy, while passive power uses the user's everyday actions without conscious intervention and therefore causes the user less discomfort. The two most common types of piezoelectric materials are PVDF (polyvinylidene fluoride) and PZT (lead zirconate titanate). There exist three different ways to excite a piezoelectric material in order to generate electrical energy: compression, slapped and bent (Van-Donk, 2000). Table-2 lists piezoelectric properties of PVDF and PZT. A piezoelectric generator produces high voltages at low currents whereas electronic circuits require low voltages at high currents, and therefore a step down transformer is employed.

Table-2. Piezoelectric characteristics of PVDF and PZT. (Van-Donk, 2000).



Property	Units	PVDF	PZT
Density	g/cm^3	1.78	7.6
Relative permitivity	$\varepsilon/\varepsilon_0$	12	1700
Elastic modulus	10^{10}N/m	0.3	4.9
Piezoelectric constant	10^{-12}C/N	$d_{31}=20$ $d_{33}=30$	$d_{31}=180$ $d_{33}=360$
Coupling constant	CV/Nm	0.11	$k_{31}=0.35$ $k_{33}=0.69$

Results of a uniform cantilever shows a non-uniform distribution of strain in the piezoelectric material while a suitably tapered cantilever formation can ensure uniform strain. This was investigated in an early work by (Glynne-Jones *et al*., 2001) the device demonstrated a reasonable amount of power for a given volume of piezoelectric material using a tapered cantilever.

Human body emits energy as heat. Therefore, heat can be harvested from human body to supply energy to portable devices. However, the device efficiency puts an upper limit on the heat energy that can be recovered. The temperature difference between the human body and the environment, e.g. low room temperature (20^0 C) can be harvested.

Steady state mechanical energy harvesting systems

Sources of ambient energy which are steady state are light (solar), wind and air currents and hydro (water flow). A photovoltaic cell has the ability of converting light energy into electrical energy (Raffaelle *et al*., 2000) each cell consists of a reverse biased PN junction, in which the light crosses with the heavily conservative and narrow N region. Photons where the light energy exists are absorbed with- in the depletion region, generating electron-hole pairs. The built-in electric field of the junction immediately separates each pair, accumulating electrons and holes in the N and P regions, respectively, establishing an open circuit voltage. With a load connected, accumulated electrons travel through the load and recombine with holes at the P-side, generating a photocurrent that is directly proportional to the light intensity and independent of the cell voltage. Photo detectors can convert light into electrical signal for wide applications in many fields, such as imaging techniques, light-wave communications, and memory storage and optoelectronic circuits. Figure-7 shows a common photovoltaic (solar) system.

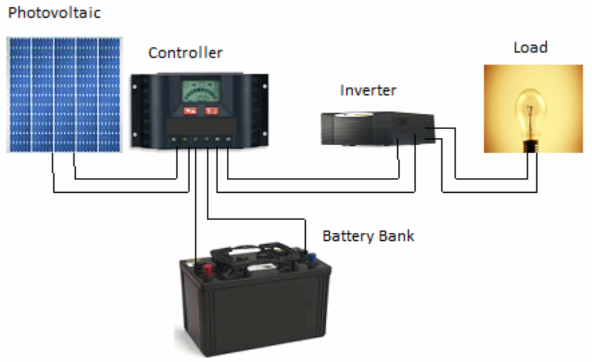
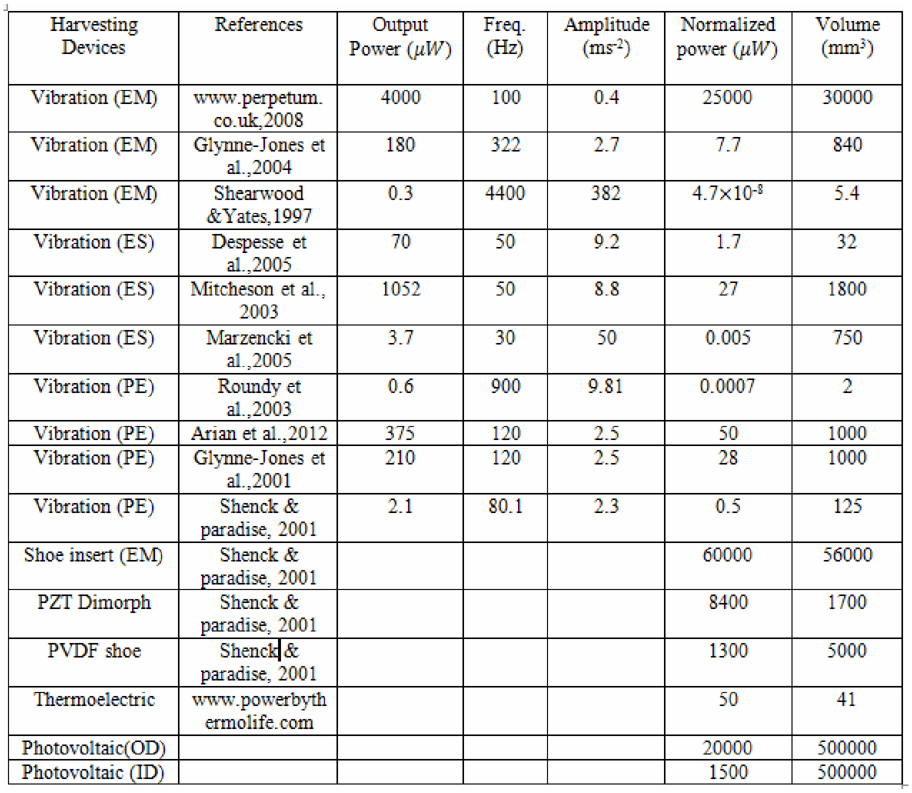


Figure-7. Photovoltaic (solar) power system.

It would be good if the system could use a light tracker for maximum power tracking, in addition, for power optimization, a maximum power point tracking design to draw maximum power from the photovoltaic system was model by (Adulkadir *et al*., 2012) and (Adulkadir *et al*., 2012). The photovoltaic device is been use for proper demonstration. Several research efforts conducted so far have demonstrated that photovoltaic cells can produce sufficient power to maintain a micro system. Moreover, a three-dimensional diode structure constructed on absorbent silicon substrate helps increase efficiency by significantly increasing the exposed internal surface area of the device (Sun *et al*., 2005). Overall, photovoltaic energy conversion is a well-known integrated circuit compatible technology that offers higher power output levels, when compared with the other energy harvesting mechanisms. Nevertheless, its power output is strongly dependent on environmental conditions; in other words, varying light intensity. Solar cells are mature and well characterized technology. Finally, a comparison of available mechanical energy harvesting systems in terms of their power output is given in Table-3. EM: electromagnetic, ES: electrostatic, PE: Piezoelectric, OD: outdoor and ID: indoor.

Table-3. Comparison of mechanical energy harvesting devices.



Harvesting Devices	References	Output Power (μW)	Freq. (Hz)	Amplitude (ms^{-2})	Normalized power (μW)	Volume (mm^3)
Vibration (EM)	www.perpetum.co.uk,2008	4000	100	0.4	25000	30000
Vibration (EM)	Glynne-Jones et al.,2004	180	322	2.7	7.7	840
Vibration (EM)	Shearwood &Yates,1997	0.3	4400	382	4.7×10^{-8}	5.4
Vibration (ES)	Despesse et al.,2005	70	50	9.2	1.7	32
Vibration (ES)	Mitcheson et al., 2003	1052	50	8.8	27	1800
Vibration (ES)	Marzencki et al.,2005	3.7	30	50	0.005	750
Vibration (PE)	Roundy et al.,2003	0.6	900	9.81	0.0007	2
Vibration (PE)	Arian et al.,2012	375	120	2.5	50	1000
Vibration (PE)	Glynne-Jones et al.,2001	210	120	2.5	28	1000
Vibration (PE)	Shenck & paradise, 2001	2.1	80.1	2.3	0.5	125
Shoe insert (EM)	Shenck & paradise, 2001				60000	56000
PZT Dimorph	Shenck & paradise, 2001				8400	1700
PVDF shoe	Shenck & paradise, 2001				1300	5000
Thermoelectric	www.powerbythermolife.com				50	41
Photovoltaic(OD)					20000	500000
Photovoltaic (ID)					1500	500000

CONCLUSIONS

The possibility of overall dependence on ambient energy resources may remove some constraints required by the limited reliability of standard batteries. Self-powered energy harvesting system can provide an extended lifespan and support to conventional electronics systems. The comparison has shown that Mechanical (vibration) energy is the most ubiquitous and accessible energy source in the surroundings. Researchers involved in this paper will learn different Sources of mechanical Energy Harvesting systems. In addition, new research can identify and compare various ambient energy sources and design unique energy harvesting system that can be useful to mankind. Each potential application must be evaluated to determine where power might be derived. As the devices scavenge for power at the edges of feasibility, the future is bright for self-powered energy harvesting system.

As the power requirements for integrated circuits continue to fall, more and more applications will become feasible candidates for self-power energy harvesting. The vision driving many researchers is that the world is filled with tiny autonomous sensor systems which can be discovered and utilizes.

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