Recent Advancements in Sources of Energy Harvesting

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Abstract— **For the last couple of decades batteries continue to be source of energy for most mobile, embedded and remote system applications. Now with ubiquitous computing requirements in the field of embedded systems, wireless sensor networks and low power electronics such as MEMS(MicroElectroMechnical Switch) devices, alternative sources of energy are required, so that these compact devices can operate without batteries for a lifetime. Self-powered devices are need of the time. The process of extracting energy from the surrounding environment is termed as Energy Harvesting.**

Keywords—Energy Harvesting, Different sources, Generation principle, Comparison

I. INTRODUCTION

There is reduction in size and expansion in functionality of Electronic devices as time passses. This is the age of wearable devices and not for portable ones. These wearable devices are very compact in size and have low power consumption and high functionality. Although the size of electronic circuit and energy needed to perform a single binary function has been drastically reduced during the last decade, all of these devices based on microelectronics, require external power supply, which is the major limitation in the mass use of the wearable devices. Advances in low power design in electronics opens the possibilities to harvest energy from environment to power electronics circuits. Block diagram in Fig.1 shows the elements of a harvesting system.

2. ENERGY HARVESTING SOURCE

Broadly energy harvesting sources are classified in two categories. One is energy harvesting from Environment and other from Human body. However their working principles are somewhat similar but their physical phenomena are different. Table 1 shows the classification of energy harvesting sources.

S.NO.	Energy Source	Type of Energy
1.	Environment	Kinetic Thermal Radiation
2.	Human	Kinetic Thermal

Table 1. Classification of energy harvesting devices

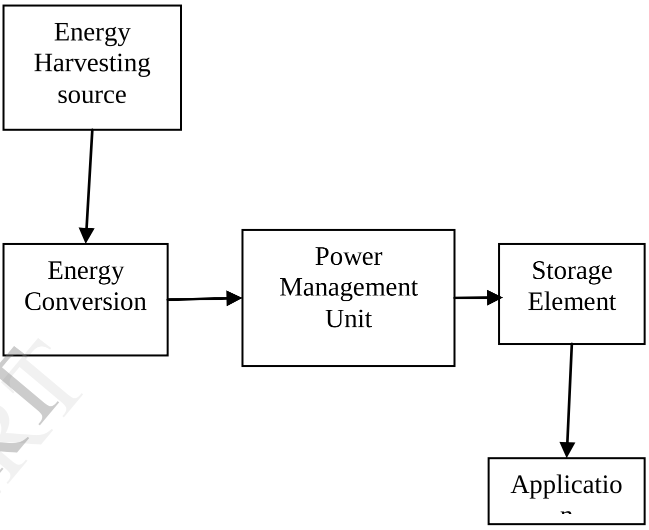

Fig.1. Outlines of the basic principle.

.2.1 Photovoltaic Cell

The working of Photovoltaic cell or Solar cell is based on photovoltaic effect. This effect states that as photons strike at the PN junction absorber layer, electrons moves to conduction band and exit through the connecting wires to create electricity (flow of current). These photons are nothing but tinny energy packets of sunlight. In[1] a solar energy harvester is described which is shown in Fig. 2.

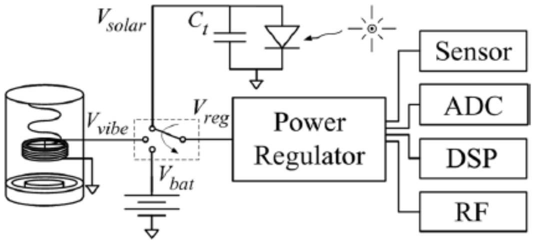

Fig.2. Low power wireless system powered by energy harvester and a standby battery and a MUX switch is used between unregulated energy sources

As shown in Fig. 2 there are two harvesters i.e $V_{vibration}$ (mechanical) and V_{solar} (photo diode). During night when solar energy is not available then mechanical source of energy can be used or standby battery can be used. Design of photodiode is shown in Fig. 3.

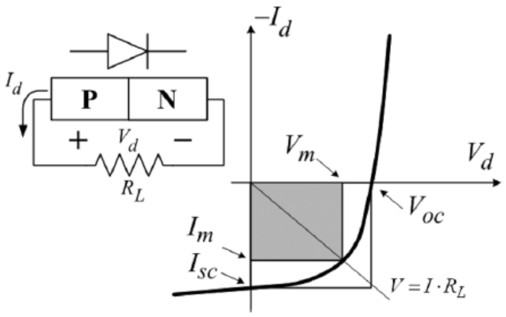

Fig.3.Typical characterstics of a photodiode under illumation . The optimum configuration for harvesting energy is found with load resistance $R_L$that maximizes the product of the current through the diode I_m and voltage across the diode V_m

As the photons strike at p-n junction then electrons are released from valance band and go to conduction band and the current flows. There must be a capacitor to store this charge. As the photodiode used in this application is integrated so that capacitor must be on the same chip. Then this stored charge is used for developing voltage for further data processing.

2.2 Mechanical Vibration

When a device is subjected to vibration its mass can be used to generate movement and this relative movement can be used to generate electricity in three modes i.e: Piezoelectric, Electromagnetic and Electrostatic.

2.2.1 Piezoelectric Energy Harvester

Piezoelectric effect is a phenomenon in which mechanical strain is converted into electric field in that material. When mechanical strain is applied to Piezoelectric material mechanical work done is stored in the form of elastic strain and some in the form of electric field associated with the induced polarization of the material. Most of the Piezoelectric materials used are ceramics, lead, zirconate, titanate etc. Basic principle of Piezoelectric transducer is shown in Fig. 4.

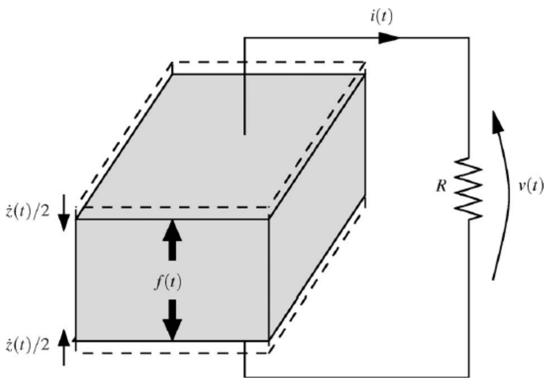

Fig.4. Basic principle of piezoelectric transducer

Another application of Piezoelectric Energy Harvester in auto-mobiles is described in [2]. The measurements show the peak to peak voltage level generated by the three different road surfaces which is from 2-10 V. It has been seen that grade E road generates much higher power than grade A surface and significantly higher than grade C. It is just because of large vibration level in grade E than in grade A road. Power output from different road surfaces is given by:

Average output power from Grade A road surface 1.1μW

Average output power from Grade C road surface 5.2μW

Average output power from Grade E road surface 13.3μW

2.2.2 Electromagnetic energy harvesting

Electromagnetic energy harvesting is achieved by the principle of electromagnetic induction which is shown in Fig. 5. This principle states that if there is change in magnetic flux passing through the conductor then voltage is generated.

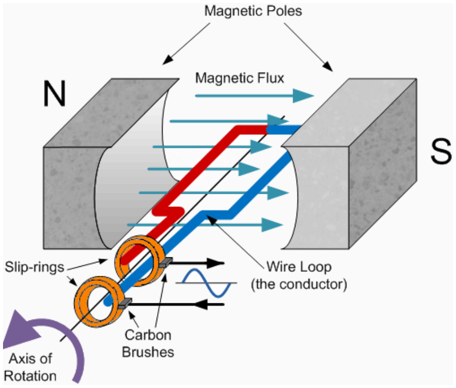

Fig.5. The basic principle of electromagnetic induction

This electromagnetic induction principle was first discovered by Faradey in 1831.The conductor was used in the form of a coil which is placed in a magnetic field and electricity is produced in the conductor by the movement of magnet or coil because of change of magnetic flux. Generated power depends upon:

I. Strength of magnetic field.
II. Relative Velocity
III. No. of turns in the coil.

2.2.3 Electrostatic Energy Harvester

S. P. Beeby et.al.[3] have emphasized that a capacitor is made up of two conducting plates which are separated by insulator or vacuum or air. If battery of voltage V charges the capacitor then there will be equal and opposite charge Q on both conducting plates. This charge remains stored when voltage source is disconnected. Capacitance of such capacitor is given by :-

$$C = Q/V$$

Where C => capacitance in farads

Q=> Charge on plates in Coulombs

V=> Voltage on the plates in volts

Capacitance of parallel plate capacitor is

$$C = \xi A/D$$

Where ξ=> Permittivity of insulator material. Fm^{-1}.

A => Area of crossection of plates. m^2.

d => distance between plates. m.

Dielectric constant of insulator material

$$K= \xi/\xi_0$$

Where ξ_0=> permittivity of free space.

Putting in the expression, we find

$$C=K\xi_0A/d$$

Also

$$V=Qd/K\xi_0A$$

Energy stored in a capacitor with plate charge Q and Voltage V is :

$$E=0.5QV=0.5CV^2$$

$$=0.5Q^2/C$$

If Q is constant then perpendicular force between plates is :

$$F=0.5Q2d/\ \ A$$

If V is constant then perpendicular force between plates is given by:

$$F=0.5\ \ AV^2/d^2$$

The work done against electrostatic force between plates provides the harvested energy.

Electrostatic generators are classified into three types:

1. In- Plane overlap Varying

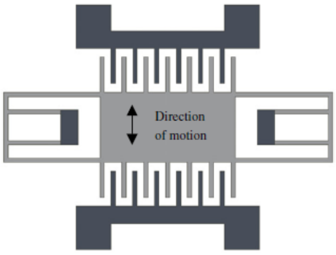

Fig.6. In- Plane overlap Varying

2. In –Plane gap closing

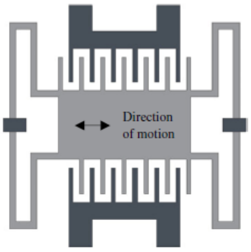

Fig.7. In –Plane gap closing

3. Out-Of-Plane gap Closing

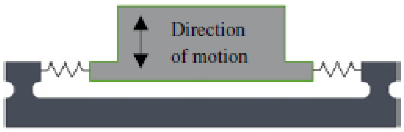

Fig.8. Out-Of-Plane gap Closing

Firstly mechanical vibrations are converted in relative motion between two elements then it will convert into electrical energy so it becomes mechanical – electrical converter as shown in Fig. 6,7 & 8 there is a mass spring system that amplifies the relative movement of mass to harvest electrical energy.

2.3 RF source of Energy Harvesting

RF (Radio Frequency) is an efficient and almost continuously available source of energy harvesting. There are more than 4 lakh Cell Towers in India from which electrical energy can be harvested. So RF can be prove an alternate source of energy haresting. Basic block diagram of RF energy harvestin system is given in Fig. 9.

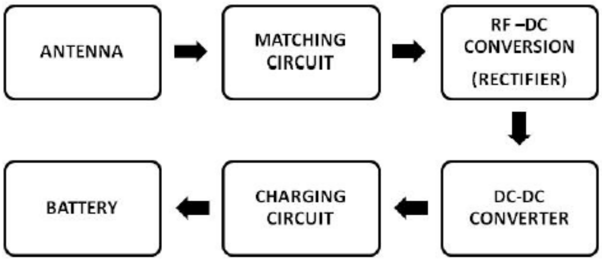

Fig. 9: Basic block diagram of RF energy harvesting system

In [4] far field powering for wireless mobile sensors is discussed. In this exact location of mobile sensor is not fixed and it is impossible to change the batteries of such sensors. In this paper far-field powering for wireless mobile sensors is used. In case of a far field of a cell tower electromagnetic waves are incident on the antenna and the power density in the range of 20-200μW/cm^2. The block diagram of such a sensor platform is shown in Fig 10.

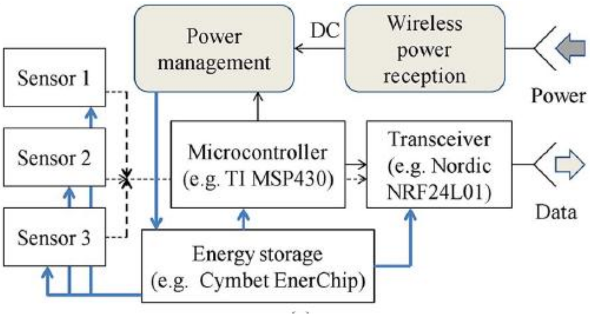

Fig.10. Block diagram far field RF powered wireless sensor

Efficiency of far field powering is a product of rectenna (antenna with integrated diode) efficiency and converter efficiency and can be written as:

$$\eta= \eta_R.\ \eta_c=(\ P_{R,dc}\ /\ P_{RFinc}).(\ P_{harv}/P_{R,dc})=P_{harv}/P_{RFinc}$$

where $P_{R,dc}$→DC power output of the rectenna.

P_{harv}→DC power delivered to the storage element.

P_{RFinc}→Incident power on rectenna of geometric area A_G given by

$$P_{RFinc}=s.\ A_G$$

Where S=S(θ,ϕ) is the angle dependent incident power density of one or more plane electromagnetic waves and in this paper it is assumed to be less than 200μW/cm^2. To obtain total incident power, the total power density is integrated over a sphere. To obtain rectenna efficiency DC output voltage is measured across the load resistance R_L.

$$\eta_R=P_{R,dc}/P_{RFinc}=(V^2_{dc}/R_L).(1/ s.\ A_G)$$

S→Power density at normal plane wave incidence, assuming a single transmitter in the far field. Multiple transmitters can be used to add their DC output from superposition of plane wave. In literature [4] various definitions are used for the rectenna efficiency as:

$$\eta_1=(V^2_{dc}/R_L).(1/ s.\ A_{eff})$$

and

$$\eta_2=(\ V^2_{dc}/R_L).(1/G_TG_RP_T)(4\pi R/\gamma)^2$$

where G_T→ Gain of transmitting antenna

G_R→ Gain of receiving antenna.

P_T→Transmitted power from transmitting antenna

The efficiency η_1 is higher than η_R because $A_{eff}< A_G$ for any antenna. Also these definitions of efficiency do not account for the mismatching of antenna to the rectifier. Table gives the simulated estimated efficiencies over a range of incident power densities.

Efficiency Definition	$S=25\mu W/cm^2$	$S=75\mu W/cm^2$	$S=200\mu W/cm^2$
η_1	48%	55%	60%
η_2	45%	53%	56%
η_R	44%	51%	54%

Table 2. Comparison of three rectenna efficiency definitions for 1.96GH$_Z$ Patch antenna.

2.3.1 RF Energy Harvesting from Cell Towers

RF is also an important source of energy harvesting. Some of most prominent RF sources are [5]:

TRANSMITER	**Frequency-Range**
FM Radio System	88-108MH$_Z$
TV Transmission	180-220 MH$_Z$
AM Transmission	540-1600 MH$_Z$
Wi-Fi	2.45 GH$_Z$, 5.8 GH$_Z$

Cell towers transmits in the frequency range of 869-890 MH$_Z$ in CDMA, 935-960 MH$_Z$ in GSM900, 1810-1880 MH$_Z$ in GSM1800 band. It transmits 10 to 20 W per carrier and there are 3 to 4 carrier and 3 to 4 operators on a single tower. Gain of cell tower transmitter antenna is typically of the order of 17dB. The half power beam width (HPBW) of antenna in horizontal direction may be between 60 to 90 and in vertical direction varies between 5 to 10. When receiver is in the main beam then maximum power is received. For GSM900 band signal strength is calculated at different distances as shown in Table 3.

This strength is calculated by Friss-transmission equation:

$$P_r=P_tG_tG_r[\lambda/(4\pi R)]^2$$

Where P_t → Transmitted Power

P_r→ Received Power

G_t→Gain of transmitting antenna

G_r→Gain of receiving antenna

R→ Distance between transmitting and receiving antenna

Distance(m)	200	100	50	10	5
Number of carriers	1	1	1	1	1
Number of Operators	1	1	1	1	1
Power Received(mW)	0.13	0.50	6.03	50.28	201.12
Power Received(dBm)	-9.01	-2.99	7.81	17.01	24.01

Table 3: Power received from cell tower(GSM 900 band)

Receiving antenna gain is taken as 9dB according to fabricated microstrip antenna gain. Transmitted power is 20W from the cell tower frequency is taken as 950 MH$_Z$ which is approximately middle value of GSM900 band.

2.4 Thermoelectric Energy Harvester

Thermoelectric effect is the direct conversion of temperature difference between two metallic junctions to potential difference and vice versa. It is well known that if two conducting materials are joined and if between the junctions there is a temperature difference then voltage is generated. This is called See Beck effect. Thermoelectric generator and thermo couple devices are based on this principle.

Thermo electric generator can be used for the natural temperature difference between air and soil to generate electric energy [6]. Prior to this, thermo electric generators used were very large, thermo couples that worked on high temperature difference and gave low specific power density.

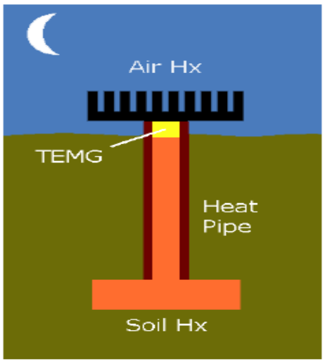

Fig: 11. Simplified diagram for energy harvesting device. “Heat exchanger” abbreviated as” H$_x$”

That is why these are not suitable for low voltage applications. So current research focuses on the micro generators, which gives high specific power densities for low temperature differences. One example of such a thermo electric micro generator is presented in Fig. 11. Such devices can produce about 22 mW of electrical power during one charge cycle.

One more example of thermo electric generator which is given in Fig. 12 [7]. In this type of generator P type and N type semi-conductor materials, called thermo element are connected in series and placed in parallel along the hot and cold junction. As there is difference in temperature of hot and cold junction so electronic potential is generated at the junction (of p-n type material) and as the circuit is a closed loop, so power is extracted across load resistance R_T.

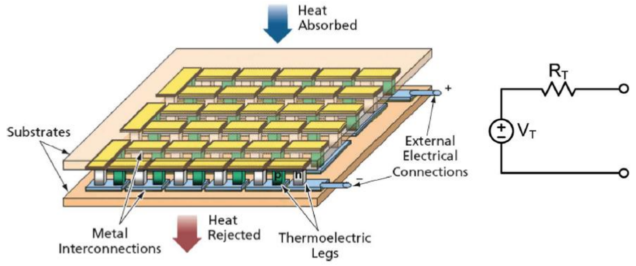

Fig: 12. A typical thermoelectric generator and its equivalent electrical circuit.

Figure of merit of TE=$(\sigma S^2/\beta)T$ [8]

Where S=> Seeback coefficient [V/K]

β => Thermal conductivity .

σ=> Electrical conductivity .

T=> Absolute Temperature.

Most of the time p and n type bismuth telluride material is used for building thermo electric generator as they have very good thermal properties. We can generate 0.2 mv/k by a single p-n junction. But it is very low amount of voltage. To boost the output voltage level we can use multiple or many p-n junctions between two high thermal conductivity substrates. Generally human body and associated sensors can work with a small degree of temperature difference. The voltage generated is also very small. As a typical example a 10 cm^2 device composed of p-n type material can produce 25 mV/k so total junction voltage can be 50-75 mV but this is not sufficient amount of voltage to run a CMOS circuitry.

2.5 Wind Energy

Wind energy is the energy from flowing air caused by temperature (therefore pressure) difference in the atmosphere. Radiation from the sun heats up the air, forcing air to rise. Conversely where temperature falls, low pressure zone develops. Winds (that is airflow) balance out the difference. So wind energy is solar energy converted into kinetic energy of moving air.

As the wind flow is captured by turbines, it is converted into rotational movement which subsequently drives a conventional generator for generating electricity. A large amount of literature [9] available on wind energy but that is in the MW range. The authors in reference [9] have described a wind generator whose output voltage is small enough to drive a wireless sensor node. Functional diagram of wind energy harvester for a wireless sensor node is shown in Fig.13.

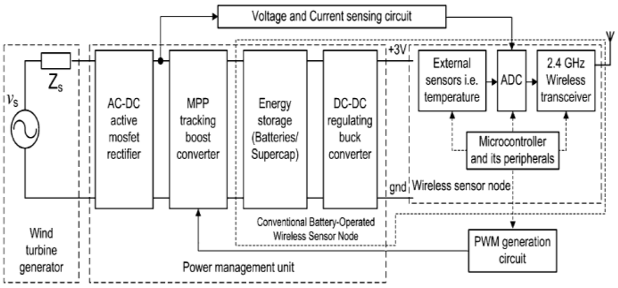

Fig: 13. Functional diagram of Wind Energy Harvester wireless sensor node

In this application micro wind turbine generator with horizontal axis is used. The output power available in wind is given by:

$$P_{wind} = 1/2PAV^3$$

Where V→ input wind speed

A→Given wind front contact area.

Figure 14 shows the wind speed in the month of June at sample remote area which shows average wind speed is around 3.6 meter/second.

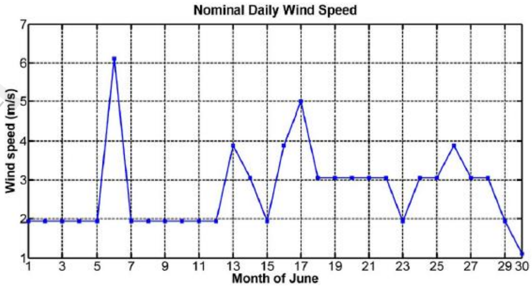

Fig: 14. Nominal monthly wind speed in a typical deployment location over a period of 30 days

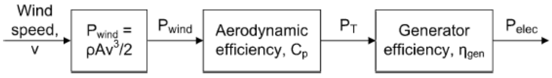

Fig: 15. Functional block diagram of wind turbine generator

Fig.15 shows power available at different stages of wind energy generator such as P_{wind} is wind power, P_T is mechanical power, $P_{Electrical}$ is electrical power. When wind flows through the blades of wind turbines then some amount of power available in wind is harvested as electrical power. It is experimentally tested that with average wind speed of 3.6 m/s the power co-efficient (C_p) for wind turbine is 39 percent. By using all the technical specifications the mechanical power P_T is given by:

$$P_{T,3.62m/s} = C_p P_{wind}$$

$$= 1/2(0.39)(1.225)[\ (0.03)^2](3.62)^3$$

$$= 32mW$$

This mechanical power P_T is the power available at the rotor shaft which is directly coupled with the electric generator. The electric power P_{elec} harvested by the turbine generator is given by:

$$P_{elec,3.62m/s} = \eta_{gen} P_{T,3.62m/s}$$

=(0.41)(32mw)=13.12mW

As shown in Fig. 14 wind speed varies from 2.3-7 m/s so the output power also varies 2-70 mW. So there is need for proper matching between wind speed and load resistances for maximum power transfer and improve the boosting topology which is described in next section.

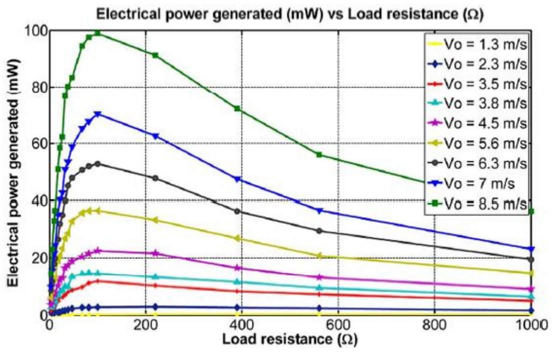

Fig: 16. Power curve of wind turbine generator over a range of load resistances

2.6 Sound Energy

Sound energy is very less discussed and less developed. Electric energy can be generated from sound energy by means of piezoelectric materials. So direct conversion of sound energy to electric power is not possible. It is done as: sound→Mechanical→Electric Power. G. R. A. Jamal et.al. [10] have given an example of such type of electric power generation from noise. The mechanical energy of sound is absorbed by piezoelectric material with good piezoelectric characteristics as a result voltage is generated, but this amount of voltage generated by single unit is very small so in this paper multiple piezoelectric materials are used as shown in Fig 17:

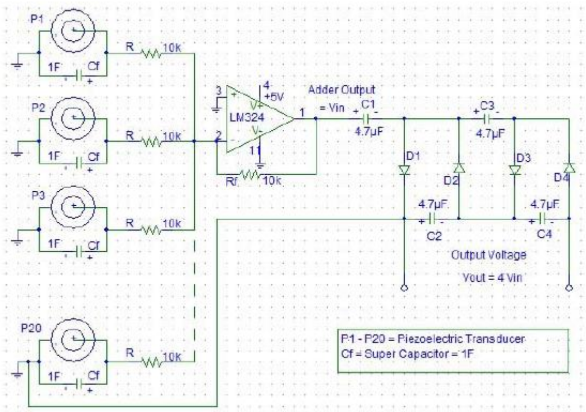

Fig: 17. Full circuit set up for sound energy to electrical power conversion

In this experiment buzzer is used to generate sound energy, which is used to produce small electrical energy at the terminal of piezoelectric transducer. One fared super capacitor of 5.5 volt is placed in parallel with piezoelectric terminal for filtering and storing purpose. Single unit can generate around 200mV, but it is very small amount of voltage. To increase the output voltage 20 units of piezoelectric transducer, buzzer and super capacitors are put in parallel. Then an Opamp (LM324) is used to add the voltage generated by all the 20 units. At the output of Opamp, 4V is produced. But still this voltage is not enough to drive a device or circuit. So some boosting or voltage multiplier is used, then 12V is generated at the output. Here a 9V battery is used to store the generated voltage as shown in Fig: 17.

S.B. Horowhz et.al [11] have described a micromechanical acoustic sound energy harvester for energy harvesting is given in Fig. 18.

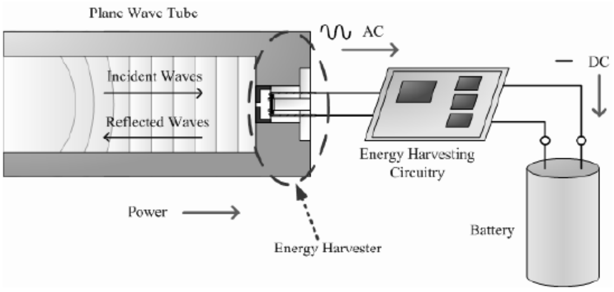

Fig: 18. Schematic of overall acoustic energy harvester

There is a piezoelectric circular diaphragm connected with a wave tube. This diaphragm converts acoustic to mechanical and then mechanical to electrical power with improved fabrication. It can generate 252µw/cm^2.

2.7 Energy harvested from human body

These days there is an increasing interest in the field of implantable biosensors. If energy harvested techniques are used with these biosensors then the lifetime of these sensors can be increased because there is no need of battery recharging. In case of biosensors this energy can be harvested from the human body itself by the following ways:

2.7.1 Thermoelectric Effect

Scavengers exploiting thermal gradients to generate energy are based on the Seebeck effect. Due to temperature difference between two different metal junctions or semiconductors, a voltage drop is created across them. Human body continuously radiates heat. This waste heat can be used for generation of electric energy. The energy harvesting method by human body is distinguishable in two manners [12]:

1. **Active Method:** In this method the user has to take additional action to generate power for powering electronic devices.
2. **Passive Method:** In this method user has no need to take additional action or no need to change his habit to generate power for powering electronic devices.

Various methods to harvest energy for biosensors [13]:

2.7.2 Fuel Cells

A fuel cell is an electrochemical device that generates current through the reaction of two chemical species flowing into it—the fuel on the anode site and the oxidant on the cathode site. The main difference between a fuel cell and a traditional battery is that the former can produce energy virtually without stopping, as long as the reactants continue to be present.

2.7.3 Infrared Radiation

These kinds of harvesters exploit an external infrared (IR) source to transmit power to an implanted photodiode array; this array converts the received radiation into a current to properly charge the sensor battery as shown in Fig.19.

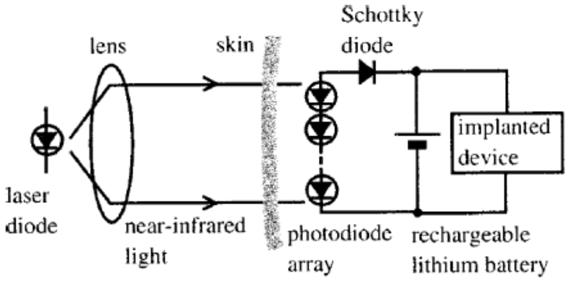

Fig: 19. Example of Infrared energy harvester

2.7.4 Inductive Links

The use of inductive links to power implanted sensors has been deeply investigated in the last decade. An inductive link consists of two coils. The primary coil is placed outside the body, generating a variable magnetic field by means of an alternate current flowing in it.

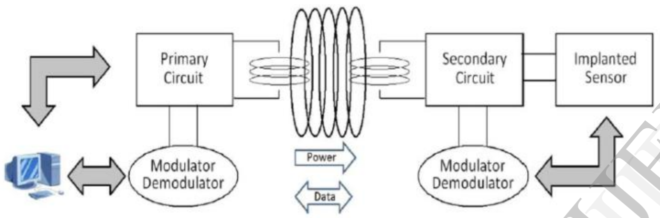

Fig: 20.Schematic representation of an inductive link performing bidirectional data transmission.

The change of the magnetic flux through the secondary coil generates an electromotive force across it, according to the Faraday–Neumann–Lenz law

$$\xi = d\phi_\beta/dt$$

where ϕ_β is the electromotive force generated by the change of the magnetic flux through the secondary coil. An inductive link representation is shown in Fig. 20.

2.7.5 Low-Frequency Magnetic Fields

This kind of harvester uses low-frequency magnetic fields placed outside the body to move an implanted magnetic rotor and to generate power exploiting its mechanical rotation as shown here in Fig21.

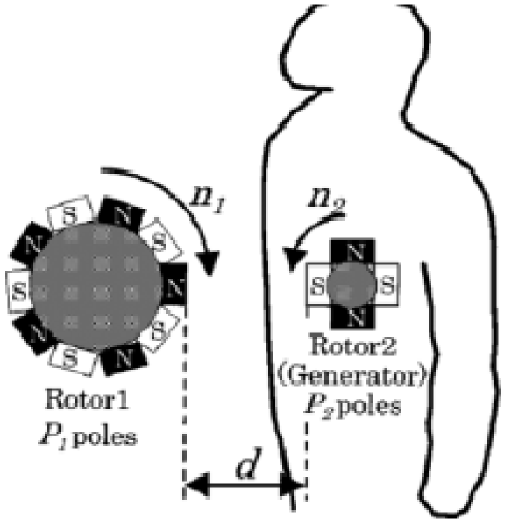

Fig: 21. Low-frequency magnetic fields are used to move an implanted rotor to generate power.

Comparison of different sources

Energy Harvesting Sources	Merits	Limitations	Output Power Density
Photovoltaic Cell	1.Small in size 2.Power density is high	1.Power supply depends upon weather condition.	15mW/cm^2 [14]
Piezoelectric Energy Harvester	1.Does not need a separate voltage source. 2.Compatible with the MEMS.	1.Brittle in nature 2. Sometimes allows the leakage of charge.	13.3µW [2]
Electrostatic Energy Harvester	1.Has ability to integrate with microelectronics 2. Does not need any smart material.	1.They need an additional voltage source to initially charge the capacitor.	70µW [3]
Electromagnetic Energy Harvester	1.improved reliability 2.Reduced mechanical damping.	1.Bulky in size 2.Complicated to integrate with MEMs.	400µW [3]
RF Energy Harvester	1.It is an almost continuous source. 2. It protects people living in close vicinity of the tower from radiation health hazards.	1.It is difficult to build a high gain antenna. 2.Power density is low.	0.87V [5]
Thermoelectric Generator	1.Produces relatively more power than piezoelectric devices. 1.Low maintenance And high reliability.	1.Low energy conversion efficiency. 2.High Cost	1.8V [7]
Wind Energy Harvester	1.Does not require any voltage supply	1.Since it involves moving mechanical parts, it can be noisy. 2.Less reliable as wind speed is not uniform.	7.86mW [9]

Sound Energy Harvester	1.Available almost at all the places and in the crowded areas this is available in large amount. 2.Does not require any voltage supply	1.Sound is not uniform at all the places and all the time. 2.Power density is low so multiple harvesting units are used.	200mW [10]
Energy From Human Body	1.Generally used for biosensors. 2.Patients do not feel inconvient in the procedure of changing the battery.	1.A lot of risk involved so a standby battery is required 2.sometime patient feels inconvenient if one part of harvester implanted inside the body stops working.	0.37W [13]

Table: 4.Comparison of Different energy harvesting sources

CONCLUSION

With a few limitations such as low amount of power generated using the power harvesters, the researchers are working towards innovative techniques. These methods would help in placing the energy harvesters as one of the best sources to portable power devices in the field of wireless technology. As most of the applications are focused on monitoring, the distributed sensing seems to enable the parameterization of the physical environment and the integration of it to established forms of information propagation (like the internet). Apart from these, adding the parameter "mobility" creates another dimension to the information system.

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