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Energy Harvesting Applications using Piezoelectric Sensors

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ABSTRACT: With the current scenario of global warming and with the rapid depletion of energy resources, the world is on a brink of an energy crisis. In the wake of this, renewable energy seems to be the only escape from this ever so looming crisis. Fossil fuels are a depleting resource of energy. The world is slowly but surely moving towards renewable forms of energy. In third world countries, large population is another problem along with an already existing energy crisis that requires an urgent solution. Renewable energy although developed to some extent is inefficient and cost ineffective. Developing countries like India are looking for solutions to help reduce to load on non-renewable energy (fossil fuels). To solve this problem the use of piezoelectricity and piezoelectric power generation may be used for power generation and energy and harvesting. The researchers would like to propose some new applications of Piezoelectricity, which do not yet exist and may be implemented in the near future to solve the energy crisis in India. These solutions involve use of mechanical energy and convert it into electrical energy. This mechanical energy may be obtained from various sources, manmade as well as natural as explained in detail with calculations in this paper.

KEYWORDS: Piezo-electric Sensors, Power Generation, Applications.

I. INTRODUCTION

Piezoelectricity refers to the buildup of energy or an electric polarization exhibited by non-centrosymmetric crystals when subjected to stress that is mechanical in nature; conversely, the generation of strain in such crystals is in reaction to an implemented voltage. In contrast, when an electrical field is applied to such a material it will produce a mechanical strain in it that is proportional to the electrical field subjected to it. They transform power from mechanical to electric and vice versa. The occurrence described is called the converse effect and is utilized for sensing functions and for actuating applications. The previous is referred to as the direct effect and is used in sensing dynamic stress modifications, changes in acceleration (from shock or vibration), and the change in force applied. Considering this, researchers have observed piezoelectric properties in hundreds of ceramic and plastic substances.

II. RELATED WORK

Electricity generation using Piezoelectric sensors has been a topic of research since a very long time. Pavegen Systems, a technological company has already developed pavement slabs for conversion of energy from people's footsteps into small amounts of electrical power. They have been put to use in office spaces in London. Many papers and research journals have published works related to Piezo sensors for a long time. A paper titled Energy Harvesting using Piezoelectric Materials, was published in Special Issue of International Journal of Computer Applications (0975 – 8887) during International Conference on Electronic Design and Signal Processing (ICEDSP) 2012. The paper addresses questions such as the use of Piezoelectric sensors as well as its working and a couple of applications.

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The paper starts with introduction followed by the fundamentals of the Piezoelectric sensors. Application of Piezoelectric sensors such as the Moonie Harvester (Energy harvesters in shoes) as well as Pavegen Tile has been mentioned in the Paper as well. The paper also proposes various applications of Piezosensors in a college campus.

Since the paper talks about applications of the sensors in foot, tiles and vehicles, there was potential for finding new applications of Piezoelectric sensors. In our day to day life, almost every little thing exerts some kind of pressure on one thing or another. The most common example was our own feet. But that application has already been discussed and put to use. Another common example is that of a cupboard door. A cupboard door, when closed, exerts pressure on the bod frame of the cupboard. There are many such places where Piezoelectric sensors can be used. Hence, we tried to address this and came up with a couple of new applications of Piezoelectric sensors which we have discussed in this paper.

III. PIEZOELECTRIC MATERIALS

Piezoelectric materials can be classified on basis of two criteria crystals and ceramics. Piezoelectric materials can be man-made or may occur naturally. Some of the most important naturally occurring Piezoelectric materials are as follows:- Quartz, Topaz, Sucrose, Rochelle Salt, Tourmaline-group minerals, Lead titanate, Berlinite. The piezoelectric properties are attributed to the lattice structure of these elements. There are also other biological materials that exhibit piezoelectric properties. The Bone, Silk, Wood, DNA, Dentin, Tendons, and Viral proteins are some of the biological materials exhibiting piezoelectrical properties. Piezoelectric materials can also be synthetically created such as the following synthetic crystals:- Langanite, Lithium tantalite, Lithium Niobate, Gallium Orthophosphate. In order to have piezoelectric properties, the crystals must be non-ferroelectric and polycrystalline.

IV. PROPERTIES OF PIEZOELECTRIC SENSORS

There are many piezoelectric materials available but, not all of them are suitable to be used in the sensing elements and as transducers in piezoelectric transducers. Natural crystals, Synthetic single crystals, piezoelectric ceramics, and thin films can be used in piezoelectric transducers.

The substances that can be used as piezoelectric transducers must have the following properties:

- 1) They must have a high sensitivity (Piezoelectric)
- 2) They must have very good mechanical strength
- 3) They must be rigid, having a high Youngs Modulus
- 4) They must have high electric insulation resistance
- 5) Hygroscopicity must be at the minimum
- 6) Electric polarization and Mechanical Stress must have a linear relationship
- 7) Hysteresis must not be present
- 8) They should have low production cost and easy machinability
- 9) Anisotropy of mechanical properties must be low
- 10) They must have a low temperature dependence of all the properties within a large range of temperature.

A Piezoelectric sensor is defined as a device that is used in the measurement of parameters such as changes in temperature, strain, acceleration and pressure by converting them into an electrical charge.

V. OPERATING PRINCIPLE

In most of the crystals present naturally the unit cells are all symmetrical, but, in piezoelectric materials this isn't the case. The piezoelectric crystals though are electrically neutral with an equal number of positive and negative charges placed strategically to balance each other out. When the crystals are deformed by application of a force on them then the positive and negative charges are imbalanced due to the change in its shape. This produces a chain reaction and causes a net positive and negative charge (voltage) on opposite ends of the crystal.

VI. TYPES OF PIEZOELECTRIC SENSORS

There are three main types of piezoelectric sensors:

- 1) Sensors that measure acceleration that is piezoelectric accelerometers
- 2) Sensors that measure force, that is piezoelectric force sensors
- 3) Sensors that measure Pressure, that is piezoelectric pressure sensors

The piezoelectric accelerometer is used as it uses less power and has a wide range of frequency. Piezoelectric force sensors are used to generate a voltage in accordance to the force and hence providing a reading. The piezoelectric pressure sensor can be used to measure the changes in pressure in a liquid or gas. There are two main categories on which piezoelectric sensors can be classified:

- 1) Mechanical Sensor
- 2) Electronic Sensor

The mechanical sensors have different elements such as a diaphragm, a resistor with 3 terminals that is used as a voltage divider, a rod and a DC voltage source. When pressure is applied the diaphragm moves the connecting rod which actuates the potentiometer this generating an output voltage.

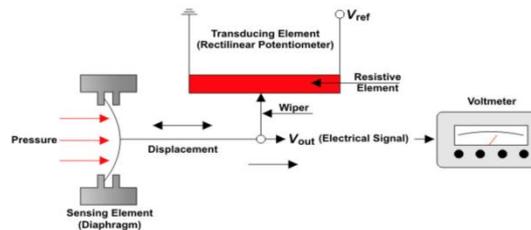


Figure 1: Mechanical Sensor

In the figure shown above, we have a mechanical sensor which senses the pressure first with the help of a Diaphragm which acts as a sensing element. When the pressure is applied, wiper which has been attached to a displacement element gets displaced in proportion to the amount of pressure applied on Diaphragm. Wiper is then connected to a transducing element, sometimes a Rectilinear Potentiometer as shown in the figure which has a resistive element which is used to detect the voltage change which in turn is measured by a Voltmeter.

Another type, the electric piezoelectric sensor has a different operating principle. The diaphragm here is replaced by a piezoelectric material such as PVDF (polyvinylidene difluoride).

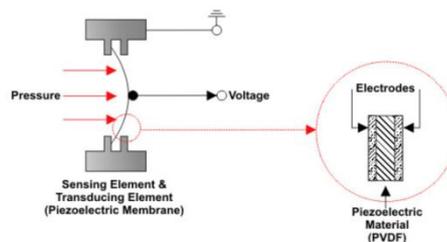


Figure 2: Electronic Sensor

In the figure shown above, the PVDF is present in between two electrodes. This PVDF behaves as a transducer and as a sensor. When pressure is applied on the diaphragm, the pressure is converted directly into a voltage and the potentiometer component is bypassed.

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VII. AIM AND OBJECTIVE OF THE PAPER

The newly developed concept of energy harvesting talks about capturing small amounts of energy that may be in the form of vibrations or maybe lost to the environment such as process surpluses such as mechanical vibrations, heat loss, sound energy and light energy. This captured energy maybe reused to improve electrical efficiency of the devices, provide better performance and potentially even replace batteries for low powered electrical devices. Piezoelectric materials provide revolutionary development in this field. When subjected to mechanical stress, a piezoelectric material experiences a change in its lattice structure that leads to ionisation of positive and negative charges across the ends of the crystal. Put simply, this means, mechanical energy that would otherwise be wasted is utilised into useful electrical energy. Devices maybe constructed that store this energy in a battery and maybe further utilised for meeting the energy requirements.

Listed below are the components utilized for the setup of the paper:

- 1) Piezoelectric Film Sensor
- 2) Capacitor
- 3) Resistor
- 4) Rectifier (Single Phase Bridge Rectifier)
- 5) Relay
- 6) LED
- 7) Voltage regulator (LM7805)
- 8) Diode (IN4007)
- 9) Microcontroller (ATMEGA328)
- 10) Transistor (Amplifier)
- 11) LCD Display
- 12) Printed Circuit Board
- 13) Battery (Lead Acid 12V)

VIII. PCB (PRINTED CIRCUIT BOARD)

A Printed Circuit Board is a main component that provides the basic framework for the assembly of all the electronic components. PCBs provide a compact and rugged support for all the components required for a specific electrical application. It eliminates the need of using wires. It reduces the complexity of construction and intermingling of wires by providing a neat and tidy framework. Components need to be soldered to the PCB. It consists of conductive tracks that are etched out of layers of copper sheets stacked upon each other. The copper sheets are laminated between layers of non-conductive substrate. Specialised CAD software such as Autodesk EAGLE is used to design the layout as well as the schematics required for manufacturing of a PCB. But the file which has been generated in EAGLE isn't readable by the CNC machine. Hence it is required to import the file into another software called CopperCam which then converts the EAGLE file into a "Gerber" file which is readable by the CNC machine. In CopperCam, various commands of the CNC machine are generated according to the machining process required for each part/layer of a PCB.

In the figure shown below is of a PCB circuit. The Green Screen on the PCB is to display information. In case of a step sensor, it displays the number of steps as well as the amount of voltage generated in each step. All the subcomponents such as the Capacitor, Transistor, Diode, Rectifier, etc. are fitted on the PCB of the apparatus.

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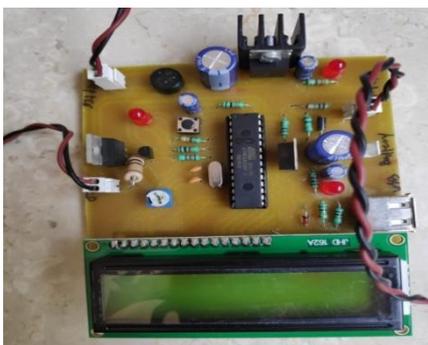


Figure 3: PCB Used in the Paper

IX. WORKING

The Footstep power generator works on the principle of piezoelectric effect. Piezoelectric Effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress. Thus, squeeze certain crystals (such as quartz) and you can make electricity flow through them. In most crystals (such as metals), the unit cell (the basic repeating unit) is symmetrical; in piezoelectric crystals, it isn't. Normally, piezoelectric crystals are electrically neutral: the atoms inside them may not be symmetrically arranged, but their electrical charges are perfectly balanced: a positive charge in one place cancels out a negative charge nearby. However, if you squeeze or stretch a piezoelectric crystal, you deform the structure, pushing some of the atoms closer together or further apart, upsetting the balance of positive and negative, and causing net electrical charges to appear. This effect carries through the whole structure so net positive and negative charges appear on opposite, outer faces of the crystal. Normally, the charges in a piezoelectric crystal are exactly balanced, even if they're not symmetrically arranged. If you squeeze the crystal (massively exaggerated in this picture!), you force the charges out of balance. Now the effects of the charges (their dipole moments) no longer cancel one another out and net positive and negative charges appear on opposite crystal faces. By squeezing the crystal, you've produced a voltage across its opposite faces and that's piezoelectricity! In this paper the researchers have used the same phenomenon of producing piezoelectricity from piezoelectric crystal in the form of coin shaped disc. When one steps on the weighing machine the piezoelectric disc gets compressed. After the leg is lifted the crystal is decompressed. Thus a full vibration is sensed by the crystal disc and a voltage across it is produced. This voltage is sensed by the voltmeter and displayed on its display. Also, at the same time this voltage is used to charge the 12VDC Battery. LED's have been mounted under the weighing machine that is switched on by relay through 555 timer IC whenever a voltage is generated. This event is notified by a glowing LED on the PCB. (Also one can hear the switching sound of the relay). Thus, whenever a person walks through the weighing machine the battery gets charged due to the voltage which is also displayed on the voltmeter. This event is notified by glowing LED's beneath the weighing machine.

X. PROCEDURE

The researchers drew the basic circuit diagram to connect the various components and sensors. Once the circuit diagram was drawn the components were joined using wires. Attached the sensors to the circuit and tested the concept by attaching an LED that would light up if the concept is found to work. Then the need to calculate the values arose and the researchers decided to make a compact and robust circuit hence decided to make a Printed Circuit Board for the paper. To construct the PCB, the schematic diagram was first constructed using Autodesk Eagle software. Once the schematic diagram was completed it was converted into the circuit diagram of the PCB top using Autodesk Eagle. This file was then transferred to another software called Coppercam which converts the files exported by eagle into CNC readable format, commonly known as "gerber file". The gerber file consists of various layers of schematics depending upon the type of machining process required for manufacturing the PCB. For example: milling, drilling and grinding. Once the PCB is manufactured the components such as the capacitors, resistors and LED need to be installed

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on it. This is done by fitting the components in the PCB in accordance to the schematic diagram and then soldered to the PCB. Once the components are soldered the Piezoelectric sensors are attached in series having one common input and output for all of them. Once the sensors and components are attached the chip on the PCB must be programmed to show the desired output on the LCD and measure the voltage generated by the sensors. The Atmega328 chip is programmed using the Arduino open source programming software. Once the chip is programmed the model is now ready for testing. The adapter is plugged in to power the LCD and the chip. The power is switched on and one can check if the model is working correctly. Once the model is tested and found to be in working condition the footstep voltage may be measured by operating the model. The experimental values are noted. After repeated testing the results are noted and are used for calculations. The values are used to calculate energy that may be generated for the proposed applications.

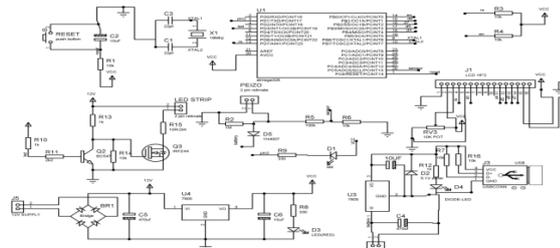


Figure 4: Schematic Diagram

In the figure above, we have a schematic diagram of the PCB which is the first step in making the PCB. It is used to arrange the components on the PCB in a proper format. It is like a basic electric diagram of the PCB.

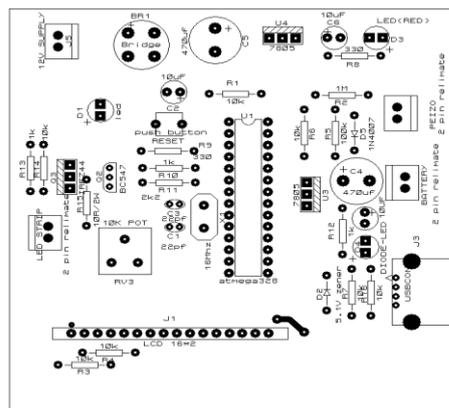


Figure 5: PCB Top Diagram

In the figure above we have a top diagram of the PCB which is made in the software and then used for printing purposes. The above diagram is the CAD version of the schematic diagram shown earlier. It is done so that the CNC machine is able to read to file and perform operations accordingly.



Figure 6: The Printed Circuit Board

In the figure above, we have a CNC machined Printed Circuit Board. It is made in the CNC machine which is made as per the schematics of the top diagram of the PCB as shown earlier.

XI. FOOTSTEP POWER GENERATION

This concept is the simplest and most basic application of the above made model. In populated countries like India there are a lot of people that frequent important public places such as train stations, public transport platforms and footpaths. This energy can be utilised by the model proposed to generate and store energy in batteries and use the energy as and when required. Piezoelectric plates may be installed on the stairs and platforms in public places like railway stations and the movement of people in these places will cause the piezo-sensor to contract, thus producing current that gets slowly stored in a battery. The batteries may be connected to lighting systems that may be operated at night.

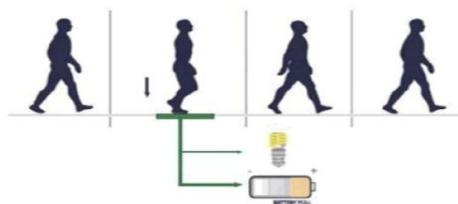


Figure 7: Footstep Power Generation

In the figure above, we have a man walking over a tile which has Piezoelectric Sensors fitted to it. As the man walks over the tile, it gets pressed in and electricity is generated which in turn glows the light bulb. This diagram shows the basic functioning of a Piezoelectric sensor in Footstep Generation.

CALCULATION:

In 1 square feet of area, the researchers have assembled 8 piezo-electric sensors. Piezo sensor's power generation varies with different steps.

Min. voltage measured – 1V.

Max. voltage measured – 10V.

It took an average person of 70 kgs, 120 steps to increase 0.1 V charge in the lead acid battery. Thus considering the lower efficiency of a piezoelectric sensor by considering the weight of an average person to be 50 kgs, 1200 steps are required to increase 1 V of charge in a battery.

Hence, to increase 12 V charge in a battery:

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$12 \times 1200 = 14400$ steps.

Data shows that on an average about 7.5 million people commute by Mumbai Local trains daily. There are 136 local train stations in Mumbai area. Hence, number of people travelling through per station per second = 55000.

The height of the flight of stairs = 20 feet.

Height of each stair = 0.5 feet.

Therefore, number of stairs in one flight = $20 \times 0.5 = 40$ stairs.

Considering 3 platforms and 2 overbridges on each station,

Number of flights of stairs in one station = 12 flights.

Number of stairs = 12×40

= 480 stairs.

Assuming the average number of stairs in each station to be 500.

Average length of each stair = 10 feet.

Average width of each stair = 0.5 feet.

Average area available for sensors on each stair = 10×0.5

= 5 sq. ft.

Since there are 8 sensors in 1 sq. ft. of area,

Number of sensors in 5 sq. ft. of area = 40.

Average area occupied by one step of a person = 0.5 sq. ft.

But since the compression of one plate will lead to the compression of all 1 sq. ft. area of the plate, Average area occupied by one step of person = 1 sq. ft.

Assuming one step per second on any given sensor at any point of time,

Time required for 8 sensors to charge a 12 V battery = $\frac{14400}{60 \times 60}$ hours

= 4 hours.

Number of batteries charged in one day (22 hours) = $22 \div 4$

= 5.5 batteries

Let us assume that 5 batteries are charged by sensors fitted in 1 sq. ft. area.

Since there are 500 stairs per station,

Area of stairs per station = 500×5

= 2500 sq. ft.

Since there are 136 stations in Mumbai,

Area of stairs in all stations = $2500 \times 136 = 3,40,000$ sq. ft.

Hence, number of batteries charged in one day (22 hours) = $3,40,000 \times 5$

= 17,00,000.

Thus it is possible to charge almost 17 lakh batteries of 12 V rating in one day if piezo electric sensors are fitted in all Local Train Stations of Mumbai.

XII. POWER GENERATION USING RAIN FALLING ON AN UMBRELLA

This concept proposes the use of piezoelectric sensors on top of an umbrella. When rain hits the umbrella the piezo-sensors experience a mechanical force that leads to a generation of voltage. Whenever it rains heavily the rain falling on the umbrella causes the battery attached to the umbrella to charge. This may be used to charge the mobile phone of the user or may be used as a light source in the dark.

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Figure 8: Piezo-Sensor on an Umbrella

In the above figure, we have a Piezoelectric sensor connected to an Umbrella in such a way that rain drop falls on it and exerts a certain amount of pressure on it.

CALCULATION:

Average annual rainfall in India is 300-650 mm/hr.

Average raindrop diameter = 5 mm
= 0.5 cm
= 0.5×10^{-2} m

Assuming the raindrop to be a perfect sphere,

Average volume of a raindrop = $\frac{4}{3} \times \pi \times r^3$
= 0.06544 cm³
= 0.07 cm³

Average mass of a raindrop = Density \times Volume
= 1 g/cm³ \times 0.07 cm³ = 0.07 gm

Terminal Velocity is given by the formulae,

$$\text{Terminal velocity (V)} = \sqrt{\frac{2mg}{\rho AC}}$$

Where, m = Mass of raindrop

g = Acceleration due to gravity

ρ = Density of water

A = Area of raindrop

C = Drag Coefficient

Thus by substituting the values,

Terminal Velocity (V) = 0.34 m/s.

$$\text{Change in time} = \frac{\text{Diameter}}{\text{Terminal Velocity}}$$

$$= 0.015 \text{ s}^{-1}$$

Change in momentum = Mass \times Terminal Velocity = 2.4×10^{-5} kg.m/s

Average force exerted by a single raindrop on a surface = Change in momentum \div Splat time
= 1.6×10^{-3} N

Average diameter of an umbrella = 3 feet
= 0.91 m

Surface area of hemisphere = $2\pi r^2$
= 1.27 m²

Surface area of umbrella = $1/3 \times$ surface area of hemisphere
= 0.42 m²

Average area of one drop = 1.96×10^{-5} m²

Number of drops on the umbrella = 21429 drops

Therefore approximate number of drops on the umbrella = 21430.

One can fit approximately 320 sensors on an average sized umbrella.

Assuming 5 drops fall on one sensor per second,

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Force exerted by 5 drops = 0.008 N.

It is not possible for a piezoelectric sensor to register forces as low as 0.008 N. Therefore, unless and until more sensitive piezoelectric sensors are developed the above proposed application of the piezoelectric sensor is not feasible.

XIII. POWER GENERATION USING THE POWER OF WATER FALLING FROM A HEIGHT (WEIR)

This presents yet one more application of this concept that may be implemented in agrarian economies like India. Weirs commonly called “bandhaaras” are small dams constructed in villages to facilitate irrigation of crops. They are small blockages constructed across small canals or distributaries of rivers in the mainland. The piezoelectric plates may be installed at the bottom of these weirs where the water falls. The flow of water is turbulent hence will continuously generate a change in dimension of the piezoelectric crystals thus inducing current in them due to piezoelectric effect. This may again be stored in batteries and utilized for village lighting.



Figure 9: Weir

The above image shows a small weir which can be used as a potential location for fitting a Piezoelectric sensor tile. A weir is a small dam built along the breadth of a small river so that a certain amount of water can be stored and used by people living around.

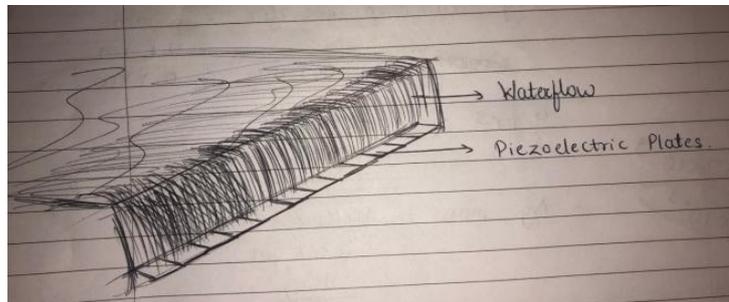


Figure 10: Proposed Position of Sensor

In the diagram shown in figure 10, we have shown the potential use of Piezo-electric sensor in a weir. We proposed that a line of tiles fitted with Piezo-electric sensors can be placed below the weir so that water falls on it. As the water falls on the Piezo sensor, pressure can be sensed and in turn electricity will be generated.

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CALCULATION:

Average length of Weir = 40 feet = 12.192 m.

Hence, packets of 8 sensors assembled in 1 sq. ft. area = 40.

Average height of Weir = 4 feet = 1.2 m.

Density of water = 1000 kg/m³

Volume of water falling upon 1 sq. ft. of plate per second = 0.11163 m³

Hence,

Mass of water = Density × Volume

$$= 111.63 \text{ kg}$$

$$= 112 \text{ kg}$$

Force exerted on 1 sq. ft. of plate per second = 1120 N.

Hence, it takes 107.16 minutes to develop 12 V of charge in the Battery by 1 sq. ft. area of sensor plate.

Total area of sensor plates = Total Length of weir × Width of 1 sensor plate

$$= 40 \text{ sq. ft.}$$

(Assuming only one layer/row of sensor plates is fitted below the weir).

Number of plates of 1 sq. ft. area below the weir = 40.

Thus, If all the plates are connected to one battery,

The amount of time required to charge a 12V battery = $107.16 \div 40$

$$= 2.67 \text{ minutes}$$

Thus approximately 3 minutes are required to charge a 12 V battery.

Hence,

In a single day, assuming that the water flows for 24 hours,

$$\text{Number of batteries charged} = \frac{24 \times 60}{3} = 480 \text{ batteries.}$$

Thus a total of almost 480 12V batteries can be charged in a single day.

XIV. CONCLUSION

The concepts of footsteps to generate energy, energy generated using an Umbrella and the energy that may be generated using the power of falling water are new and relatively easy to implement practical applications of the piezoelectric effect for energy harvesting. These concepts may well be implemented in highly populated countries like India. They installation cost would be high, being a one-time cost only. If implemented properly, it will produce virtually free electricity for applications such as powering night lights and street lights. These concepts could help the power crisis in rural India.

This paper shows tested concepts that are waiting to be applied in the real world to make an improvement in our current lifestyle as well as do our bit in caring for the environment.

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