Piezoelectric Energy Harvesting from Shoes of Soldier

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***Abstract*—In recent times low powered devices are gaining popularity, one of the main reasons being their portability and hence the demand increases for low power & portable energy sources. Apart from the conventional and non-conventional methods of generating power, researchers are finding other ways of utilizing the energy that is wasted in the environment in form of vibrations, pressure, heat, sound, etc. Thus, Energy harvesting from the environment comes out as a clean and sustainable way to power these devices. In this paper an attractive approach is proposed to harvest energy from human shoes particularly Soldier's shoe. A soldier carries numerous electronic gadgets for his mission which needs uninterrupted power supply. An alternative way is proposed here to power the Soldier's Electronic System or to recharge his batteries. This approach is implemented with the help of piezoelectric materials. The idea is to incorporate piezo polymers i.e. PVDF stacks beneath the heels of their shoes and generate electrical power merely by walking/running. This approach generates clean & green power which can even be stored for future use in absence of load. DC-DC converters were employed to maximize the electrical power from the material, to store it in a Super capacitor & to enhance the efficiency of the system. This power can be later utilized to power the soldier's electronics gadgets or and can also power a passive RF tag system for tracking soldier's in remote areas.**

Keywords*—*Piezoelectricity; Piezogenerator; PVDF; Energy Harvesting; DSSH; Buck-boost Converter

I. INTRODUCTION

The waste energy available in the environment can be exploited to generate an appreciable amount of useful power with the help of transducers. The proposed work in this paper recommends Piezoelectricity as an alternate energy source. In areas such as remote villages, forests, hilly areas, where it is difficult to access electricity, Energy harvesting technique is proposed as an alternative. There exists variety of energy harvesting techniques but mechanical Energy Harvesting comes out to be the most widely used technique. The piezoelectricity obtained needs to be optimally extracted and stored with the help of Optimal Energy Harvesting [2] and Storage techniques. These techniques will be dealt in the later part of the paper. There are two types of devices for energy harvesting. The first kind, are devices that use part of the energy of the user which are called Human harvesting devices. The second type, are the Environment Energy devices that harvest the energy from the environment.

Considering the energy levels that can be harvested from individuals, only thermal and kinetic energy can provide significant results and the effect may prove noticeable when several devices depend on the activity of a single user. Here, the main focus will be on the use Passive Kinetic Human Harvesting devices. In this paper, we discuss about the available energy from a person especially a Soldier's shoes during brisk walking and the corresponding effects on the piezo polymer mounted in his shoes. As mentioned, a soldier needs uninterrupted power supply & in this regard he carries numerous batteries to power the Electronic System which not only adds weight to his body but also require continuous charging. The soldier needs to migrate back to his troop to recharge these batteries once they are discharged. Figure 1 gives a clear view of the portable system which needs to be incorporated in the shoes of the soldier to power the devices carried by him for his mission.

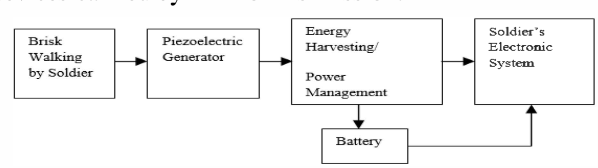

Fig. 1: Portable Piezoelectric Generator System

II. DESIGN OF PIEZOGENERATOR

A soldier needs to carry numerous armaments &gadgets in order to be prepared for his Mission. Amongst these, the Electronic gadgets need uninterrupted power supply and hence, he carries numerous batteries which not only add weight to his body but also require continuous charging.The following table (Table 1) shows around 12 equipments generally carried by a soldier on a 72 hour Mission. These equipments are supplied by a combination of 7 types of batteries as mentioned in the table. Thus, in total he carries around 70 batteries to power these equipments. The total power requirement of these equipments sumsto9160 mW.

Thus, this paper proposesan alternative source of energy for them to power their Electronic System and also to charge their batteries. In addition, this can be achieved merely by his movement during the mission. The paper proposes a Piezoelectric Energy Harvester that can be incorporated in the shoes of the soldier. The Harvester is

978-1-4673-8587-9/16/$31.00 ©2016 IEEE

based on a specially designed sandwich structure with an appropriate thickness in order to allow compatibility with the shoe & to provide comfort to the soldier wearing it.

A. Material

The Piezoelectric Energy Harvester can also be referred to as the Piezogenerator as it generates electricity popularly known as the Piezoelectricity. The Harvester comprises of a no. of layers of piezoelectric materials. These materials exhibit piezoelectric effect which refers to a change in electric polarization that is produced in certain materials when they are subjected to mechanical stresses. This stress-dependent change in polarization manifests as a measurable potential difference across the material. Referred to as the direct piezoelectric effect, this phenomenon is observable in many naturally available crystalline materials, including quartz, Rochelle salt and even human bone. Engineered material, such as lithium niobate and lead zirconate titanate (PZT), exhibit a more pronounced piezoelectric effect. An important feature to note about this piezoelectric phenomenon is that the process is reversible. The inverse piezoelectric effect refers to a deformation of these materials that result from the application of an electric field.

In this paper, a piezoelectric polymer, PVDF (polyvinylidene fluoride) was chosen for the design of Piezogenerator. These piezo polymers are generally available in the form of films. The PVDF films were chosen in order to provide flexibility & light weight characteristics to the structure, as the structure is placed in the shoes where area is a constraint. Figure 2 shows a picture of a laminated PVDF film manufactured by Measurement Specialties with electrode thickness of 28 μm and film dimensions of 25×13×0.205 mm^3.

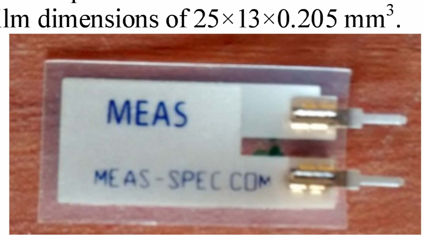

Fig. 2: PVDF Laminated Film Sensors-LDT0-028K/L w/crimps

Fig. 3: One Layer Comprising of Nine Film Sensors

The films were made into a layer where each layer consists of a matrix of 3×3 films. The films were connected by soldering in a fashion so as to increase the strain on each film with the help of wires running over them. Figure 3 gives a view of a layer. These films were stacked into six layers and each layer was insulated from the other with the help of plastic sheets which did not alter the basic nature of the films and also provided strength to the structure.

The final design implemented comprised of 6 layers wherein each layer had 9 piezo films connected in parallel to increase the capacitance value. Finally, the 6 layers were connected in series to increase the voltage output. Figure 4 represents the implementation of the final structure of Piezogenerator.

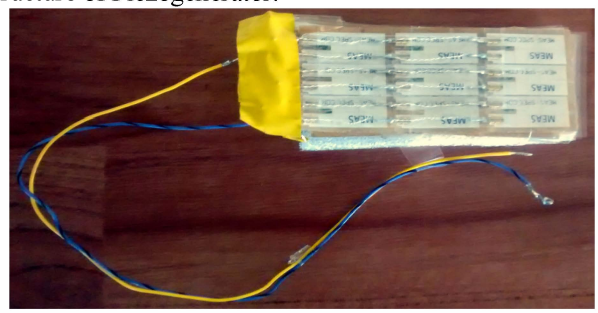

Fig. 4: Piezogenerator with Two Output Terminals

TABLE 1

Sl. No.	Electronic Device	Weight (Kg)	Operating Voltage & Current (V & mA)	Power* (mW)	Battery Used
1.	Night Vision Optics	0.048	1.5, 13.34	40	2 AA
2.	Mark VII	0.116	3.9, 42.82	167	Lithium
3.	MBITR	2.91	9.6, 69.40	5330	8 BB 521
4.	Sure Fire Light	0.1	3, 12.167	219	6 CR-123A
5.	Mag Lite	0.048	1.5, 6.33	19	2AA
6.	DAGR	0.59	1.5, 20.25	729	24 AA
7.	Head Set	0.048	1.5, 6.33	19	2 AA
8.	PEQ-2A	0.048	1.5, 3.667	11	2 AA
9.	HTWS	0.174	1.7, 33.33	680	12 AA Lithium
10.	M68 CCO(Day)	0.0032	3, 0.02	0.06	DL 1/3N
11.	LMR	2.906	9, 20.97	1510	8 NiMH
12.	P-Beacon	0.045	1.2, 40.83	49	

*Average milliWatts per 72 hours
Source: PROTONEX

B. Piezogenerator

When a soldier is walking, a compressive force is exerted on the upper plate which in turn compresses the piezo films placed beneath them. As a piezoelectric ceramic is anisotropic, physical constants relate to both the direction of the applied mechanical or electric force and the directions perpendicular to the applied force. Consequently, each constant generally has two subscripts that indicate the directions of the two related quantities. In the following configuration, it was observed that the induced polarization is in direction 3 (parallel to direction in which ceramic element is polarized) and per unit stress is applied in direction 1 (perpendicular to direction in which ceramic element is polarized). Hence, the d_{31} and g_{31} constants come into play with respect to the design. When the piezo stack or Piezogenerator is subject to a compressive force produced by foot, the layers move down and the PVDF films are stretched along 1-axis, as presented in Figure 2.

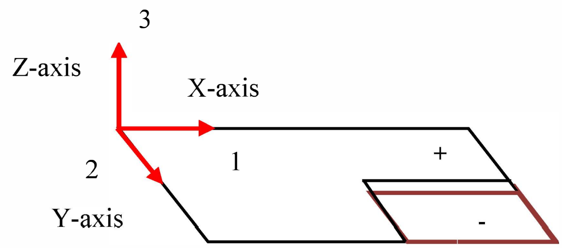

Fig. 5(a): PVDF Film

This leads to a piezoelectric field created inside every PVDF layer, driving the free electrons in the external circuit to accumulate on the upper and lower 3-axis surfaces (electrodes) of every PVDF layer to screen the piezo-potential [1]. The charges can later be collected from these two electrodes which are taken out as the output terminals. The PVDF layers are under compression only during the free fall of the foot. The stress experienced by the material is proportional to the electrical output produced by it. Hence, the film shave been improved to increase the strain on the material.

The V_p is the output voltage available from the piezogenerator at the blue & yellow wires. There are five important figures of merit in piezoelectric materials namely [3].

a. d - piezoelectric strain constant,
b. g - piezoelectric voltage constant,
c. k - electromechanical coupling factor,
d. Q_M - mechanical quality factor and
e. Z - acoustic impedance

The output of the Piezogenerator was then fed to a DC-DC Converter through a Rectifier circuit. Thus, the entire system contributes to a Portable Energy Harvesting System as shown in Figure 1.

III. Dynamics of Human Walking

The standard gait of a human involves walking at a frequency of 2 Hz i.e. 2 steps per second. The potential energy stored when the person lifts his leg can be given by

Potential energy (PE) = M * g * h (1)

Where, M stands for the mass of the body, g stands for acceleration due to gravity & h stands for the vertical displacement of the foot while walking. Thus, potential energy can be calculated that is generated by a 70 Kg person considering 5 cm or 0.05 m [21 in hp] as the vertical displacement of his heel during his walk.

Now, the available power P can be given by

P = PE*frequency (2)

P = 34.3 * 2 = 68.6 Watts

Hence, the above calculation gives us an idea about the power available at each step during walking. The following table (TABLE II) presents the same for a range of weights i.e. for different class of people.

TABLE 2

Sl. No.	Weight (Kg)	Available Power(Watt)
1.	45	44.1
2.	50	49
3.	55	53.9
4.	60	58.8
5.	65	63.7
6.	70	68.6
7.	75	73.5
8.	80	78.4
9.	85	83.3
10.	90	88.2
11.	95	93.1
12.	100	98.0
13.	105	102.9
14.	110	107.8

IV. Energy Harvesting System

The basic concept of this Energy harvesting System is to extract the maximum power available at the Piezogenerator and to provide the same efficiently at the load end for storage or load purpose. The Piezo materials will be experiencing stress when the Soldier walks and this stress will then be converted into voltage potential as it is the property of a piezo material. The electrical power available from the piezoelectric material is ac which needs to be rectified for storage purpose. Thus, voltage available at the end terminals of the piezogenerator will be pulsating in nature.

The Piezogenerator is represented by its electrical equivalent in Figure 5.As can be seen, it is a V-source V_p along with its equivalent Capacitance $C_{p,}$ connected in series representing a Thevenin equivalent circuit. The types of load can be:

a. Lighting a LED
b. Charging a set of Super capacitors
c. Powering a RF Transmitter
d. Charging a battery

The Charging of a battery or a set of Super capacitors can be used to power Electronics carried by the soldier.

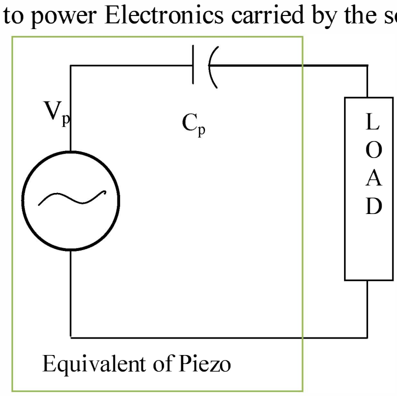

Fig. 5(b): Equivalent Circuit of PVDF Films

A. *Standard Rectifier Circuit*

The basic Energy Harvesting circuit involves a Bridge Rectifier along with filter capacitors. Since, the piezo produces an ac output which cannot be stored; the conversion to dc becomes a necessity. A Schottky diode Bridge Rectifier was employed in order to minimize the losses of conversion from ac to dc as the power obtained from the harvester will be in the order of milli Watts. The storage element considered is a series connection of 2 Super capacitors of 2.5 V, 1 F each. The Super capacitor characteristics lie between that of a Capacitor and a Battery. Thus, it is a better alternative where rapid charge/discharge cycles are needed instead of long term compact energy storage.

B. *DSSH Technique*

The standard rectifier circuit only transfers the available power from the Piezogenerator to the Super capacitor or rather the load circuit. But this power transfer is neither optimal nor efficient. Thus, a DC-DC Converter was employed to increase the efficiency of the system. Employing a Converter becomes necessary as the available voltage at the output of Piezogenerator mounted in the shoes will be very less and hence we need a Boost circuit for higher voltage and a Buck circuit for higher current.

The Figure of Merit (FOM) defined initially is weak in case of the PVDF films used for our application and hence to have an optimized energy harvesting, we choose the Double Synchronized Switch Harvesting technique.

To be able to control the trade-off between extracted energy and voltage increase, as well as the trade-off between energy extraction and damping effect (*i.e.*, the balance between mechanical energy and conversion abilities), it is proposed in this section to use a combination of series Synchronized Switch Harvesting on Inductor and Synchronous Electric Charge Extraction technique on Buck-Boost Converter popularly known as DSSH[4].The C_{int} & C_{SC} acts as the storage Capacitors. Figure 6 shows a block diagram for it.

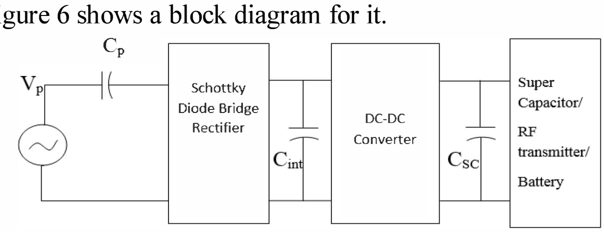

Fig. 6: Piezogenerator with DC-DC Converter

Here, the Piezogenerator is followed by a Schottky Bridge Rectifier, a Buck-Boost Converter and the load circuit. Another advantage of the DSSH is its ability to control the trade-off between converted energy and damping effect as well. Hence, thanks to its ability to control the amount of extracted energy through the intermediate electrostatic energy tank (intermediate capacitor), the DSSH technique is able to letmechanical energy enter into the system, contrary to fixed system, which, in spite of increasing the conversion abilities of materials, drastically limit the mechanical energy in the system, leading to moderate harvested energy [5].

This technique is roughly independent from the load resistor value, thus operating on a wide voltage range (while the standard technique is limited in terms of output voltage). Thus, this technique also permits a gain of more than 500% in terms of harvested energy compared with the standard energy harvesting technique [4].

The Figure 7 shows a DSSH technique on Buck-Boost Converter. It employs 2 switches S_1 & S_2 whose control principle can be decomposed into four different steps as follows [4].

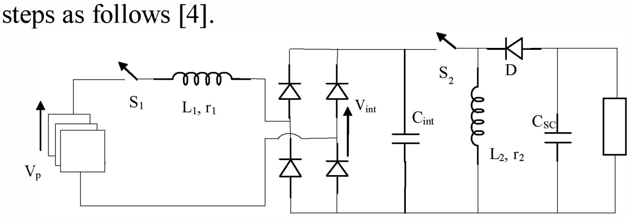

Fig. 7: DSSH Circuit Peak was Observed for a Brisk Walking at 2 Hz. The Above Results are from a 51 Kg Person Wearing the Shoes

First Step: the switches $S_1$and $S_2$are open and no energy transfers from the piezoelectric films to the load.

Second Step: when the piezoelectric voltage V_p is maximal (or minimal) detected by a peak detector, $S_1$is closed and a part of the piezoelectric energy is transferred to the intermediate capacitor C_{int} while voltage V_p is reversed, like in the case of the original Series SSHI technique.

Third Step: $S_1$is opened when change in voltage on C_{int} is zero, and $S_2$is closed until all the energy of C_{int} is transferred into the inductor L_2.

Fourth Step: $S_2$is opened and all the energy of $L_2$is transferred to the load (modelled here by a storage capacitor C_S and R).

Thus, the switching sequence is synchronized with the piezoelectric voltage (or displacement) maxima and minimas, so that the energy conversion cycle is very near to that of the Series SSHI.

Detailed analysis of the DSSH technique shows that the energy conversion is optimal when the value of C_{int} is very large compared to that of the internal capacitance of the piezoelectric element C_p in the case of very weak values of the figure of merit [2].

V. Experimental Setup and Results

One layer of Piezogenerator was implemented in the shoes and the person was made to walk at a frequency of around 1 Hz. The implementation and the results recorded in CRO are shown in Figure 8 and 9 respectively.

Fig. 8: Shoes with One Layer of PVDF Films

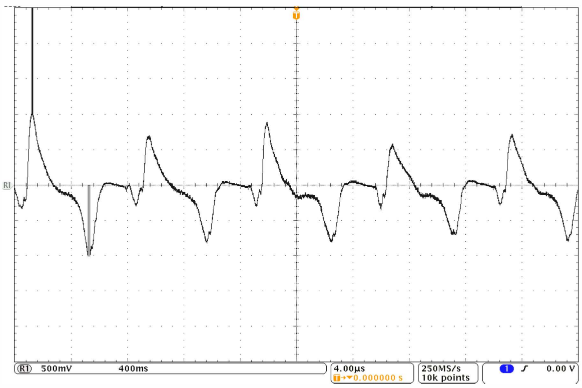

Fig. 9: Voltage Recorded was around 1 V Peak to Peak for a Frequency of 1Hz

The same experiment was repeated by implementing the Piezogenerator i.e. six layers and the waveforms recorded is shown in Figure. 10. A voltage of around 4 V peak to

The figure is divided into two parts, the upper row represents the entire waveform recorded for a period of around 10 secs of walking and the second row represents the zoomed version for a period of 4 secs.

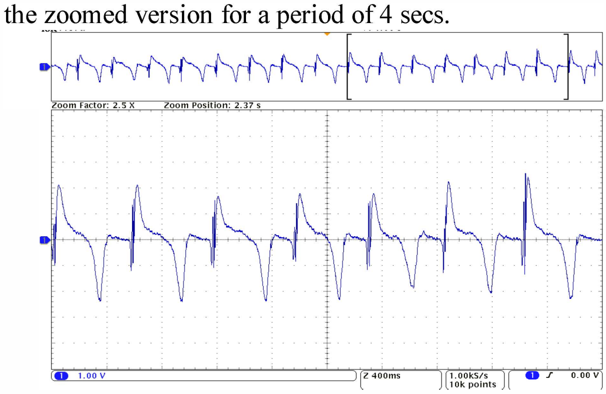

Fig. 10: Voltage Recorded was around 4V Peak to Peak for a Frequency of 2Hz (Brisk Walk)

It was observed that the output from Piezogenerator is not a pure sinusoid. Hence, the output equivalent of the Piezogenerator was given from a Function generator to a Standard Rectifier Circuit to check the charging of the Super capacitor and in turn lighting a yellow LED. The LED starts glowing at a voltage greater than 1.78 V when a 5 V peak to peak voltage input at 1 Hz is provided from the function generator.

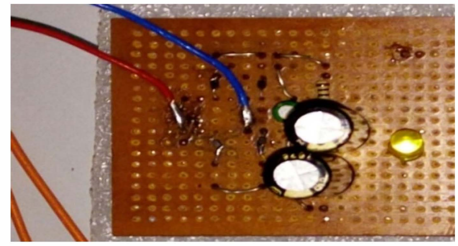

Fig. 11: Rectifier Circuit on a PCB

It took around 10 minutes to charge the Super capacitor and hence, the LED to glow. Figure 11 represents the implemented PCB circuit.

VI. CONCLUSION

The voltage level from the Piezogenerator will increase as the strain on it increases which can be achieved if the force applied on it increases. The entire energy available at the Piezogenerator was not transferred efficiently at the load circuit and hence, implementing DSSH at Piezogenerator is a better proposition. But it will come at a state of increase in the complexity and cost of the circuitry.

Thus, the piezoelectric materials will serve as an alternative in the coming future to meet the growing demand for energy. It can be incorporated at places with appreciable level of vibrations like on roads to control traffic, Speed breakers, floors and seats of a local train or on railway platforms, etc. as they can operate in a wide range of frequencies starting from 0.01 to 10^8 Hz.

ACKNOWLEDGEMENT

The authors would like to thank K. Rambabu, Dr. T.S. Balasubramanian and N. Beebama for their continuous assistance and mentorship. This research work was supported and carried out at Research Centre Imarat, Hyderabad.

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