Energy Harvesting Using Thermoelectric Materials

Submitted in partial fulfillment of the Degree of

Bachelor of Technology

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DECLARATION

We hereby declare that the project work entitled "Energy Harvesting using Thermoelectric Materials" submitted to the Jaypee Unversity of Information Technology, Solan, is a record of an original work done by us under the guidance of Dr. Shruti Jain, Assistant Professor (Senior Grade), and this project work is submitted in the partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Electronics and Communication Engineering. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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CERTIFICATE

This is to certify that project report entitled "Energy Harvesting Using Thermoelectric Materials", submitted by AASTHA AFSAR (111007), ROHIT CHAUHAN (111028), SOMYA VARMA (111128) in partial fulfillment for the award of degree of Bachelor of Technology in Electronics and Communication Engineering to Jaypee University of Information Technology, Waknaghat, Solan has been carried out under my supervision.

This work has not been submitted partially or fully to any other University or Institute for the award of this or any other degree or diploma.

(SHRUTI JAIN)

Date: 25th May, 2015

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It is said that gratitude is a virtue. This part is dedicated to special thanks that I would like to deliver to the people who help make possible the fulfillment of this project.

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ABSTRACT

Energy harvesting from human body has been undergoing an interesting and quick development thanks to the technological availability of new electronic components and the growing of different applications, in particular, for biomedical and social impacts on human beings' daily life. As energy harvesting techniques, especially thermoelectric generator (TEG) technologies, develop during recent years, its utilization in powering electronic devices is attempted from many aspects. Previous research shows that TEG as an energy harvesting method is feasible. Even though efficiencies for TEGs are as low as 3-5%with existing technology, useful electricity generation is possible due to the great amount of energy available during various human activities.

OBJECTIVE

We aim at developing a thermo electric generator which could extract heat from the human body and convert it to voltage. This module will be coupled with a heat sink which will help in maintaining the temperature gradient required to produce voltage. The module will be interfaced with an energy harvesting circuit which would store the electrical energy produced. This energy will then be used to power up devices when the conventional means to charge them are not available. The thermo electric generators perform best at higher altitudes since the temperature there is low and we don't need heat sinks to maintain the temperature gradient.

Chapter 1: Introduction

Small and cost-effective thermoelectric generators scavenging energy from the environment could potentially provide power autonomy to miniaturized and/or wearable electronic products operating at very low power. In industrial environments and in automotive applications, such compact, reliable self-powered devices with sensors, wireless link, and virtually infinite lifetime could replace sensors of today that feature huge amounts of corroding wires that will otherwise completely enmesh cars and buildings in near future. They could be used for unattended sensors placed in critical or even hazardous areas inside buildings, on/in certain pipelines, in mines, inside aircrafts, ships and cars, i.e., in the locations, where there is no (or not enough) light for solar cells. They may potentially impact fire detection, homeland security, as well as many other aspects of human life. Human beings and, more generally speaking, warm-blooded animals (e.g., dangerous and endangered animals, cattle, and pets), can also be a heat source for the devices attached to their skin.

The human body is subject to the same laws of physics as other objects, gaining and losing heat by conduction, convection and radiation. Conduction between bodies and/or substances in contact; convection involving the transfer of heat from a warm body to a body of air above it or inside the human body and here the blood, gases and other fluids is the medium, radiant heat transfer is a major mechanism of thermal exchange between human body and the surface surrounding environment. These three effects in most situations operate together. In human body, metabolic processes generate its own heat as well, similar to a heat producing engine. Human body behaviors try to be in stable state therefore, it absorbs and emits energy to be in equilibrium, stimulation is applied to the body surface, this make the activity of metabolism induced to body surface.

The operating voltages and power consumption of present –day semiconductor Integrated Circuits (IC) are continually decreasing. The International Technology Roadmap for Semiconductors (ITRS) by Semiconductor Industry Association (SIA), projects that the lowest operating voltage which was 1.0 V in 2004 will reach 0.5 V in 2016. Nano-watt and micro-watt sensor, transceiver and data logging systems are in existence today. Ultra Low Power, Ultra Low Voltage wireless sensor systems are finding use in Medical, Automotive and Industrial applications. Human body heat powered devices and appliances are no longer futuristic predictions. Future applications would include personal electronics such as mobile phones and mp3 players powered by thermo electric modules embedded into clothing.[1]

1.1 MOTIVATION BEHIND THIS PROJECT:

In recent years, energy harvesting has become a popular term in both academic and industrial world, as traditional power generation resources, such as fossil fuels and nuclear fission, are either facing global shortage crisis or simply being quite costly. In contrast, the resources for energy harvesters are usually naturally present, for instance, the temperature gradient from the combustion engine, electromagnetic energy from communication and broadcast, motion from human movement, just to name a few. Currently, areas of research interests mainly consists of piezoelectric energy harvesting, pyroelectric energy harvesting, **waste heat recovery**, electromagnetic energy harvesting, ambient-radiation energy harvesting, etc. However, current technologies of energy harvesting are capable of producing only enough power to drive relatively low-power electronics. Also, high volume applications of these technologies depend on further enhancement of the energy harvesting efficiencies.

Among all research directions, waste heat recovery (WHR) is most concerned, due to the widespread existence and high accessibility of suitable resources. According to India Bureau of Energy Efficiency, the benefits of WHR includes reduction in the process consumption and costs, reduction in pollution and equipment sizes, and also reduction in auxiliary energy consumption. While there are a number of devices to fulfill WHR, thermoelectric generator (TEG) has been utilized in most applications.

TEGs are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). Their typical efficiencies are around 5-10%. TEGs are solid-state devices which have no moving parts. Sub-branches of TEG have been developed to cater the needs of specific target applications, such as radioisotope TEG for spacecraft and automotive TEG (ATEG) for automobiles. Moreover, some house-hold applications based on bio-fuel have been realized, as well as power supply for wearable electronics.

Recently, TEG is often mentioned together with photovoltaic as promising energy harvesting device in the near future. Photovoltaic has a longer history of application. But when it comes to the effective applicable time, TEG is in fact advantageous in that it has no dependence on factors such as daylight hours and changes of seasons.

Cell-phones and laptops are becoming an integral part of our social life. For everything from playing games to cooking food, sending sms messages to attending business conferences, watching movies to doing banking; we depend on our cell phones. Cell-phones and laptops are to becoming a must moving from being a luxury. According to "The Guardian" there are 4.1 billion users of cell phones in the world, which is 60% of the world's population, proving cell phones are becoming the most important personal communication device. Just like how the cell phone is becoming an important need, it is equally important to be able to power up cell phones. According to the International Energy Agency, in 2011, 1.4 billion people around the world did not have access to electricity. There is a huge portion of world population who cannot use a cell phone due to the lack of electricity. Also during natural disasters, like tsunamisor earthquakes, power outages will happen for days. During these power outages, communication is very essential, but the main communication device, cell phones, will be useless due to the lack of power.

Our project aims at developing a cell phone charger that uses energy from the human tissue warmth to provide uninterrupted power for cell phones.[2]

1.2 GENERAL REPRESENTATION OF TEGS ON HUMANS

Although thermoelectric (TE) phenomena were discovered more than 150 years ago, thermoelectric devices (TE modules) have only been applied commercially during recent decades. For some time, commercial TEs have been developing in parallel with two mainstream directions of technical progress– electronics and photonics, particularly optoelectronics and laser techniques. Lately, a dramatic increase in the application of TE solutions in optoelectronic devices has been observed, such as diode lasers, photo detectors, solid state pumped lasers, charge-coupled devices (CCDs)and others. The progress in applications is provided by advantages of TE modules – they are solid state, have no moving parts and are miniature, highly reliable and flexible in design to meet particular requirements.

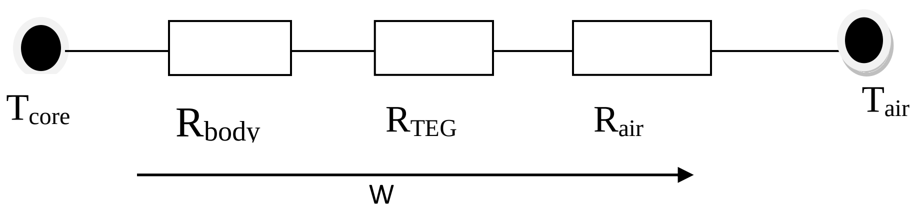


Figure 1. Simple thermal circuit representing a TEG on skin.

Figure 1 shows a simple thermal circuit representing a TEG on the skin. The heat flow ***W*** takes place in between the body with a core temperature and the ambient air with lower temperature through three thermal resistors representing the body, the TEG, and the surrounding air.

Chapter 2: Thermoelectric Generator

Thermoelectric generator (TEG) is a device that converts thermal energy directly into electrical energy. A typical TEG structure is shown in Figure 2.1. Early TEG devices utilize metallic TE material, whereas more recently manufactured TEGs use alternating n- and p-type semiconductor materials. The TEG structure is "sandwich like", with thermoelectric materials "sandwiched" by two heat exchanger plates at its two ends respectively. One of the two exchangers has high temperature, and hence, it is called the *hot side* of the TEG; while the other has low temperature and is called the *cold side* of the TEG. There are electrical-insulate-thermal-conductive layers between the metal heat exchangers and the TE material. The two ends of n- and p-type legs are electrically connected by metal.

The thermal-electrical conversion is done by a phenomenon generally referred to as "Seebeck effect", which is named after one of the scientists who discovered it. TEGs are solid-state device, which means that they have no moving parts during their operations. Together with features that they produce no noise and involve no harmful agents, they are the most widely adopted devices for waste heat recovery.

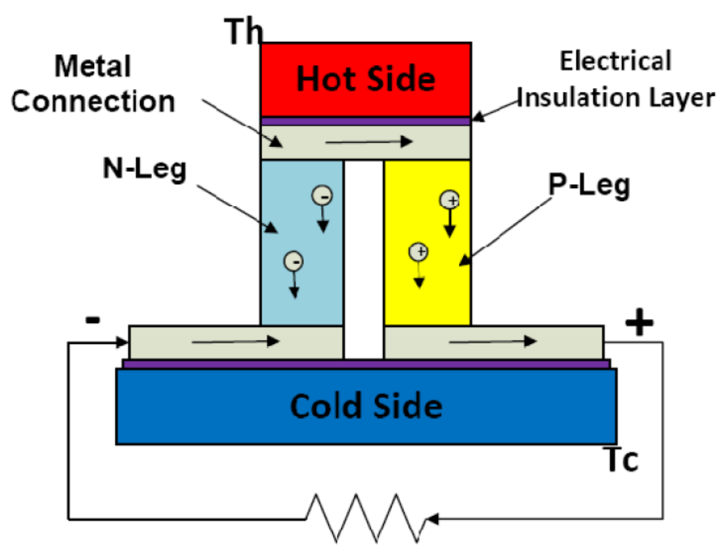


Figure 2.1 Simplified illustration of TEG.

2.1 The Physics of Thermoelectric Generation

2.1.1. Seebeck Effect

To put it in a simple way, Seebeck effect is the conversion of temperature differences directly into electricity. In the basic version of TEG, the conductor materials used to generate Seebeck effect are two different metals or semiconductors. The term *thermopower*, or more often, *Seebeck coefficient* of a material, is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material. The Seebeck coefficient has units of V/K, though it is more practical to use mV/K. The Seebeck coefficient of a material is represented by S (or sometimes σ), and is non-linear as a function of temperature, and dependent on the conductors' absolute temperature, material and molecular structure.

Table 2.1 Seebeck coefficients for some common elements [1]

Material	Seebeck Coeff.	Material	Seebeck Coeff.	Material	Seebeck Coeff.
Aluminum	3.5	Gold	6.5	Rhodium	6.0
Antimony	47	Iron	19	Selenium	900
Bismuth	-72	Lead	4.0	Silicon	440
Cadmium	7.5	Mercury	0.60	Silver	6.5
Carbon	3.0	Nichrome	25	Sodium	-2.0
Constantan	-35	Nickel	-15	Tantalum	4.5
Copper	6.5	Platinum	0	Tellurium	500
Germanium	300	Potassium	-9.0	Tungsten	7.5

In Figure 2.1, the materials used in the two legs are n- and p-type semiconductors. If we denote their respective Seebeck coefficients to be Sn and Sp, the open circuit voltage Voc generated by this TE couple is then governed by the equation:

$$V_{oc} = \int_{T_c}^{T_h} (S_n(T) - S_p(T))dT \tag{2.1}$$

If the Seebeck coefficients are approximately constant for the measured temperature range in the TE legs (which is often true), Equation 2.1 can be simplified as:

$$V_{oc} = (S_n - S_p).(T_h - T_c) \tag{2.2}$$

If the temperature difference ΔT between the two ends of a material is small, then the Seebeck coefficient of this material is approximately defined as:

$$S = \frac{\Delta V}{\Delta T} \tag{2.3}$$

where ΔV is the voltage seen at the terminals.

Thermo-power is a collective result of different effects, among which two mechanisms provide major impact, and they are *charge-carrier diffusion* and *phonon drag*.

In a TEG where two ends of the n- and p-type legs are at different temperature levels, charge carriers in the leg material tend to diffuse in the direction which can help to reach thermodynamic equilibrium within the leg. That is to say, the hot carriers (charge carriers originally at the end with higher temperature) will move toward the cold side of TEG, and cold carriers move toward the hot side. If temperature difference is intentionally kept constant, the diffusion of charge carriers will form a constant heat current, hence a constant electrical current. Take n- and p-legs of TEG in Figure 2.1 as an example, the heat source, i.e. the side with higher temperature, will drive electrons in the n-type leg toward the cold side, crossing the metallic interconnect, and pass into the p-type leg, thus creating a current through the circuit. Holes in the p-type leg will then follow in the direction of the current. The current can then be used to power a load.

If the rate of diffusion of hot and cold carriers were equal, there would be no net change in charge within the TE leg. However, we need to take into account the impurities, imperfections and lattice vibrations which scatter the diffusing charges. Since scattering is energy-dependent, the hot and cold charge carriers will diffuse at different rates, which then create a potential difference, i.e. an electrostatic voltage, in the leg. This electric field, on the other hand, opposes the uneven scattering, and equilibrium will be finally reached given enough time. The above analysis bring sabout the conclusion that the thermopower of a material depends greatly on impurities, imperfections, and structural changes, with the latter affected often by temperature and electric field.

Another major impact on thermopower is phonon drag. A phonon is a quantum mechanical description of a special type of vibrational motion, in which a lattice uniformly oscillates at the same frequency. Phonons are not always in local thermal equilibrium; they move against the thermal gradient. They lose momentum by interacting with electrons (or other carriers) and imperfections in the crystal. The phonon-electron scattering is predominant in phonon drag in a temperature region approximately defined by equation:

$$T \approx \frac{1}{5}\theta_D \tag{2.4}$$

where θ_D is the Debye temperature. This temperature is approximately around 200 K. At lower temperatures there are fewer phonons available for drag, and at higher temperatures they tend to lose momentum in phonon-phonon scattering instead of phonon-electron scattering. In the phonon-electron dominant scattering, an electron charge distorts or polarizes the nearby lattice, as it moves past atoms in the lattice. While the vibration of the lattices, i.e. phonons, will tend to push the electrons to one end of the material, losing momentum in the process. This effect leads to a decrease in the electron mobility, which results in a decreased conductivity, while at the same time contributes to the already present thermoelectric field. Since the magnitude of the thermopower increases with phonon drag, it may be beneficial in a thermoelectric material for direct energy conversion applications.

2.1.2. The Reversed Seebeck Effect

In 1834, the French physicist Jean-Charles Peltier discovered that when a current I is made to flow through the junction of two different metals, heat is evolved at the upper junction, producing a higher temperature $T1$, while a lower temperature $T2$ presented at the lower junction. The heat absorbed by the lower junction per unit time is equal to

$$Q = \Pi_{AB} I = (\Pi_B - \Pi_A) I \tag{2.5}$$

where Π_{AB} is the Peltier coefficient of the entire thermocouple, and Π_A and Π_B represent the coefficient of each material. Typically, p-type semiconductor material has positive Peltier coefficient while n-type material has negative Peltier coefficient. It is apparent that Peltier effect in fact has the reversed physics of Seebeck effect. One way to understand the phenomenon of Peltier effect is that, when electrons flow from a region of high density to a region of low density, they try to maintain electron equilibrium that existed before the current was applied, by absorbing energy at one end and emitting it at the other. A series of these thermocouples can be connected in order to enlarge the effect.

Peltier effect is most often applied to thermocouples to make solid-state heat pumps. A very popular application of Peltier effect is thermo-electric cooling (TEC).

2.2 Figure of Merit "ZT"

For thermoelectric materials, the ability to produce high energy conversion efficiency is the most important standard in determine the performance of materials. The *figure of merit* (FOM) is a very convenient measure for comparing the potential efficiencies of devices built with different materials. The FOM for thermoelectric devices is defined as

$$Z = \frac{s^2}{\kappa\rho} \tag{2.6}$$

Where ρ is the electrical resistivity, κ is the thermal conductivity, and S is the Seebeck coefficient. The conventional unit for Seebeck coefficient in calculating FOM is μV/K. More commonly used measure is the dimensionless FOM, *ZT*, where T is the average temperature ($T2$+$T1$)/2 in the device. If it is necessary to take into account both legs in the thermocouple, the dimensionless FOM can be expressed by the following equation:

$$Z\overline{T} = \frac{(S_p - S_n)^2 \overline{T}}{[(\rho_n \kappa_n)^{1/2} + (\rho_p \kappa_p)^{1/2}]^2} \tag{2.7}$$

where T is the average temperature between the hot and cold side of the device, and the subscripts n and p denote the n- and p-type semiconductor. For recently produced TE materials, ZT = 1 are considered good, while ZT values of the range of at least 3-4 is considered to be essential for thermoelectrics to compete with mechanical generation and refrigeration in efficiency.

It is obvious from Equation 2.6 that to improve the value of FOM, we can either increase Seebeck efficient, or decrease thermal conductivity. These are also the focus of current TE material research. With the advancements of nanotechnology, these targets can be achieved by manipulating the nanostructure of the materials.

2.3 TEG Materials

Metals have been the main materials used in building TEGs, until the middle of 20th century, when Ioffe noticed semiconductor materials due to their high Seebeck coefficient and their phonon-transport-dominated heat conduction. Despite metals' merit of high ratio of electrical to thermal conductivity, modern TE materials are mainly semiconductors. The performances of TEGs are largely affected by the features of materials used. Hence, the selection and combination of TE materials is vital for the design of a good TEG. It is necessary to examine and compare the existing families of TE materials. Chalcogenides material family is main contributor to TEGs, among them bismuth telluride (Bi2Te3) and its alloys are very good TE materials below room temperature. Bi2Te3 can be alloyed with Sb2Te3 or Bi2Se3 so as to considerably reduce thermal conductivity. However, since tellurium is scarce, toxic and volatile at high temperatures, its usage is limited. Lead telluride (PbTe) was found to have good thermoelectric properties at temperatures in the range of 300-700 K. Similar thermoelectric materials such as PbS and PbSe, also belong to chalcogenides system.

SiGe alloys are superior materials for thermoelectric generation and is typically used for both n- and p-legs in high temperature (>900 K) TEGs. However, the ZT of these materials is fairly low, particularly for the p-type materials.

For several materials, the figures of merits over the temperature range of 0-1000°C are shown in Figure 2.2.

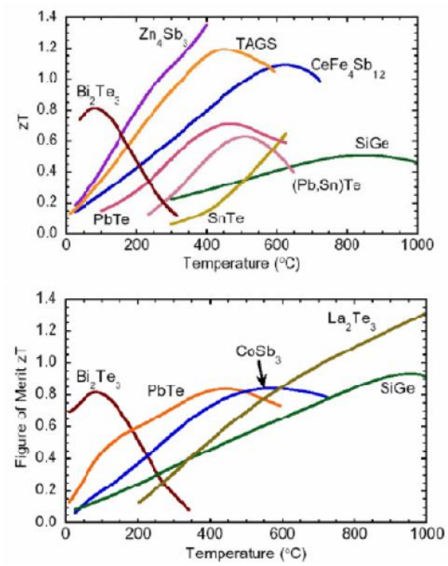


Figure 2.2 Figure of merit (*ZT*) (p-type and n-type) over the temperature range of 0-1000 °C.

2.4 TEG Architectures

The first TEG produced has the architecture similar to the one shown in Figure 2.1, with vertical structure and single material within each leg. Later, researchers realized that TE material properties are highly temperature dependent, that is to say temperature variation influence TEG performance considerably. Hence, innovated design concepts addressing the temperature-dependent issues have been developed along the way.

The first improvement in the TEG architecture comes with the concept of *segmentation* (or *stack* in some cases) of thermocouple. In this concept, it is suggested that thermocouples should be built with several materials; with each material optimized for the temperature range it is located. With this design philosophy, the TEGs could reach higher overall efficiencies than those built with single material within each leg. Main concerns are the compatibility of materials and the dimensioning of thermocouple elements.

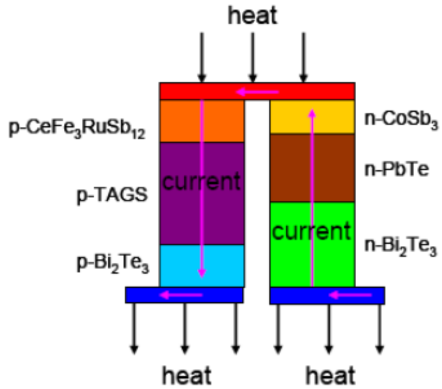


Figure 2.3 Thermocouple configuration with segmented legs.

Another concept of horizontal thermocouple configuration was proposed. The new configuration (Figure 2.3) allow each p- and n-type element to have different aspect ratios (cross-sectional area divided by thickness) so that each material layer of each element has the highest possible *ZT* for each temperature range, while at the same time, this configuration also increase the design flexibility by allowing p- and n- legs to have different thickness (length).[3]

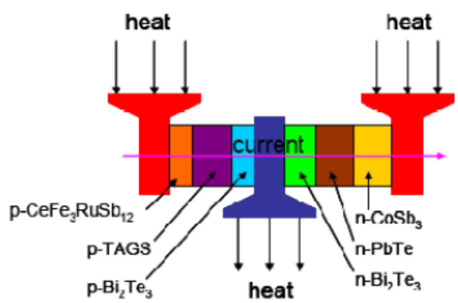


Figure 2.4 Horizontal TE couple configuration with segmented legs of different total thickness

2.5 TEC1-12706

We used the commercially available TEC1-12706 for our project. The product has the following specifications:

- Operational Voltage: 12V
- Current Max: 6 Amp
- Voltage Max: 15.2 V
- Power Max: 92.4 Watts
- Couples: 127
- Dimension; 40 X 40 X 3.5mm
- Power Cable Length: 250mm (approx)

Results obtained: The voltage obtained from the TEG was subject to various factors like the room temperature and also varies from person to person. The following are the results obtained from the TEG when measured at different surrounding temperatures and heat is provided by different persons.

Table 2.2 Current and voltage output of TEC1-12706

	Room temperature		**Cold room**	
	Voltage(mV)	Current(mA)	Voltage(mV)	Current(mA)
Person 1	185	1.6	380	3.5
Person 2	153	1.4	480	4.6
Person 3	205	1.95	430	4

Note: The readings obtained above did not remain constant for more than 30 seconds because the electrons try to maintain the thermal equilibrium so it is necessary to couple the device with a heat sink to maintain the temperature gradient.

2.6 Thermopile

A **thermopile** is an electronic device that converts thermal energy into electrical energy. It is composed of several thermocouples connected usually in series or, less commonly, in parallel. Thermopiles do not respond to absolute temperature, but generate an output voltage proportional to a local temperature difference or temperature gradient.

Thermopiles are also used to generate electrical energy from, for instance, heat from electrical components, solar wind, radioactive materials, or combustion. The process is also an example of the Peltier Effect (electric current transferring heat energy) as the process transfers heat from the hot to the cold junctions.

A **thermocouple** is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more spots, where a temperature differential is experienced by the different conductors (or semiconductors). It produces a voltage when the temperature of one of the spots differs from the reference temperature at other parts of the circuit. Thermocouples are a widely used type of temperature sensor for measurement and control, and can also convert a temperature gradient into electricity. Commercial thermocouples are inexpensive, interchangeable, are supplied with standard connectors, and can measure a wide range of temperatures. In contrast to most other methods of temperature measurement, thermocouples are self powered and require no external form of excitation. The main limitation with thermocouples is accuracy; system errors of less than one degree Celsius (°C) can be difficult to achieve.

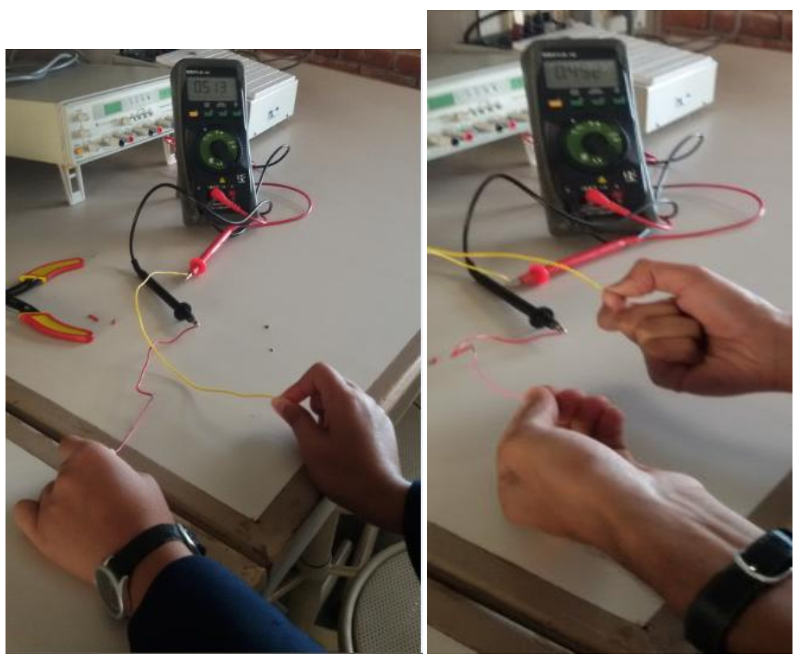
Any junction of dissimilar metals will produce an electric potential related to temperature. Thermocouples for practical measurement of temperature are junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage. Different alloys are used for different temperature ranges. Properties such as resistance to corrosion may also be important when choosing a type of thermocouple. Where the measurement point is far from the measuring instrument, the intermediate connection can be made by extension wires which are less costly than the materials used to make the sensor. Thermocouples are usually standardized against a reference temperature of 0 degrees Celsius; practical instruments use electronic methods of cold-junction compensation to adjust for varying temperature at the instrument terminals. Electronic instruments can also compensate for the varying characteristics of the thermocouple, and so improve the precision and accuracy of measurements. The ease of availability is also an important factor while choosing the materials for making a thermocouple.

We aim at making a thermocouple which uses the heat from the human body to generate electricity. First we used an aluminum wire and an iron wire of thickness 3mm to make a thermocouple but the output obtained was not sufficient to drive a booster circuit. As shown in figure 2.5 when one junction of the thermocouple was kept in a glass of ice for about half an hour the current measured was 4 micro volts. The problem we encountered was that the wire was very thick and the electrons could not align and flow because the temperature difference was not sufficient. Since we aim at utilizing the heat from our bodies this arrangement could not be used further.[5]

Figure 2.5 : Iron aluminum thermocouple with one junction in ice.

Next we used a paper clip and copper wires to make a thermocouple.

Figure 2.6. Paper clip-Copper wire thermocouple in ice



(a) *(b)*

Figure 2.7 (a) Person1heating the thermocouple (b) Person2 heating the thermocouple

The output from this configuration depends on a number of factors like:

1. The body temperature varies from person to person.
2. The room temperature
3. Area of contact

The results obtained from the thermocouple are as follows:

Table 2.3 Current and voltage output from the thermocouple

	0.4mm thickness paperclip		**1.0 mm thickness paperclip**	
	Voltage(mV)	Current(uA)	Volatge(mV)	Current(uA)
Person 1	513	4	60	-
Person 2	452	2	49	-
Person 3	400	2	41	-

Table 2.2 clearly shows the dependence of voltage generated on the thickness of the wire. It is observed that the lesser the thickness, the better is the output.

The challenge now is to step up the current so that it is sufficient to drive our charging circuit. One solution is to put a number of such thermocouple units in parallel to obtain a higher value of current which could be step up further by using a booster circuit.

Chapter 3: DC-DC Converters

DC-DC converter is a class of power converters. It converts a DC source of a certain voltage level to another voltage level. In modern electronic systems, DC-DC converters are needed to convert the voltage supply from the power source to the voltage level required by the target function block. Beside, DC-DC converter can also regulate the output voltage. For TEG utilizations in automotive applications, DC-DC converter is commonly used for boosting up voltage supplied by the TEG converted power source, so as to reach the voltage levels required by different applications.

We have discussed two of the many circuits used as voltage boosters.

3.1 Micro voltage booster

This Circuit employs a Sziklai Darlington Pair. The **Sziklai Darlington Pair**, named after its Hungarian inventor George Sziklai, is a complementary or compound Darlington device that consists of separate NPN and PNPcomplementary transistors connected together as shown below.

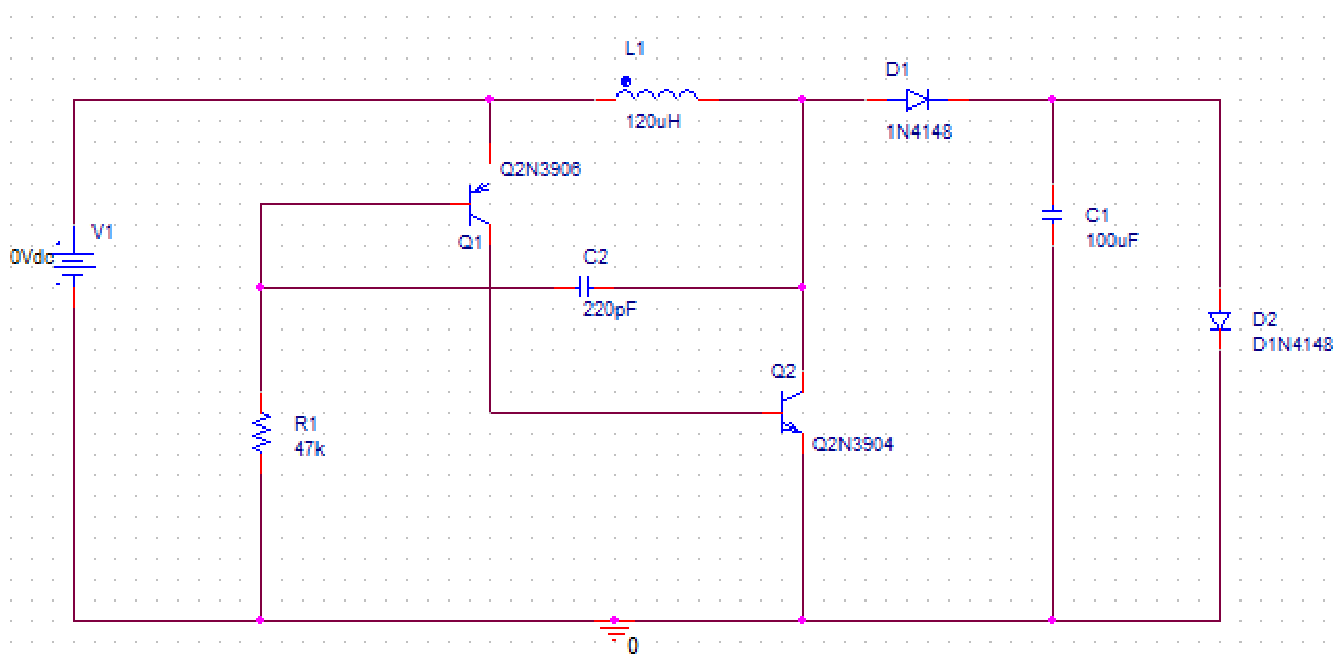


Figure 3.1. Circuit of micro-voltage booster.

This cascaded combination of NPN and PNP transistors has the advantage that the Sziklai pair performs the same basic function of a Darlington pair except that it only requires 0.6v for it to turn-ON and like the standard Darlington configuration, the current gain is equal to β^2 for equally matched transistors or is given by the product of the two current gains for unmatched individual transistors.

The circuit takes very low input values, which are stepped up to a value that is sufficiently higher than the input. To demonstrate the working of the circuit, an LED is connected across the output. Input voltage in the range of 0.6 to 1V is given. The input is boosted up and is used to glow the LED.

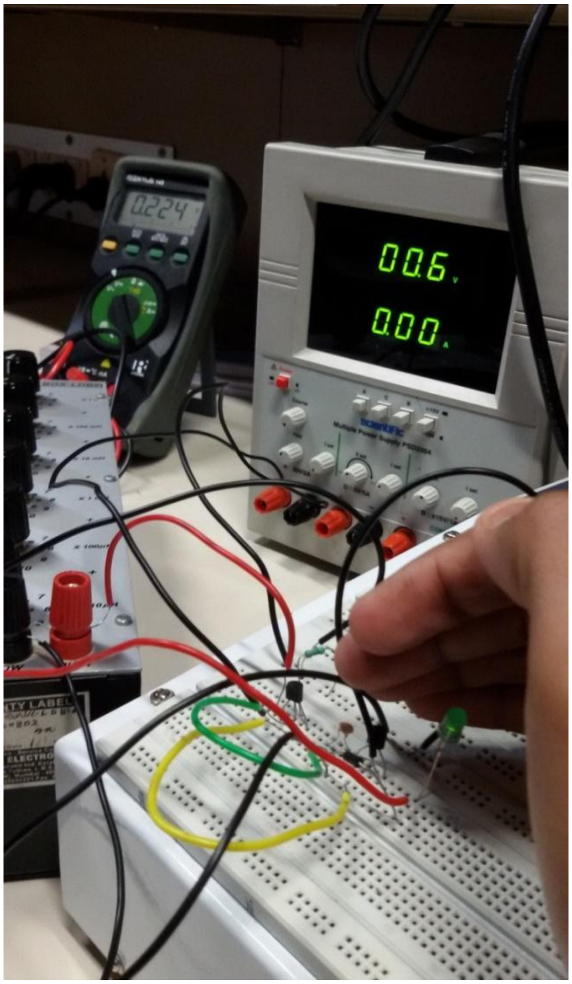


Figure 3.2 Micro voltage booster powering the LED

As it is clear from figure 3.2 above that the circuit boosts up the input voltage to a level which is sufficient to glow an LED.

The current values obtained from the circuit are tabulated below:

Table 3. Voltage vs. Current of micro voltage booster.

Input Voltage(V)	Current across the LED (mA)
1	0.9
1.1	1.2
1.2	1.5
1.3	2.2
1.4	2.4
1.5	2.7
1.6	4.5
1.7	5.3
1.8	5.9
1.9	6.6
2.0	8.3

3.2 DC-DC Converter (step up) circuit

The development of DC-DC converter used the DC input (V_{in}) = 0.3V. When switch control ($M1$) MOSFET is closed for time t_1, the inductor ($L1$) current rises and energy is stored in the inductor and if the switch is opened for time t_2, the energy stored in the inductor is transferred to load through thyristor ($X1$) and the inductor current falls.

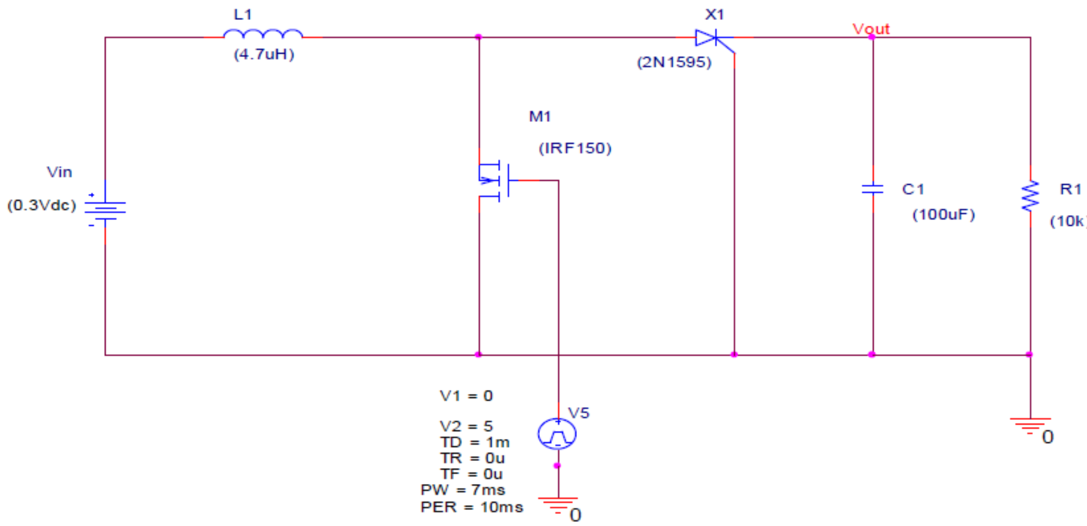


Figure 3.3. Development of DC-DC converter (Step-up) circuits.

We used MOSFET (M1) transistor and pulse (V5) is V1=0V, TD=1m, TR= 0u, TF=0u, PW=7ms, PER=10ms as a switching purpose for open and close. If a large capacitor (C1) is connected across the load, the output voltage is continuous and V_{out} becomes the average value that the voltage across the load can be stepped up by varying the duty cycle and the minimum output voltage is V_{in} when duty cycle = 0. We used inductor (L1) 4.7uH for storing the current, Resistor (R1) is 10kΩ used for the better output, we used capacitor (C1) 100uF for storing voltage and filtering of the output voltage to reduce ripple. Finally we are able to achieve the output voltage V_{out} (1.67V) after using the DC-DC converter (Step-up).[6]

Results of PSPICE SIMULATION:

The Figure 3.4 shows the output of the DC-DC converter circuit. There are two curves in the Figure. Here the curve [A] is the input of 300mV, and the curve [B] denoted is the final output of the Step-Up DC-DC converter circuit is (1.67V).

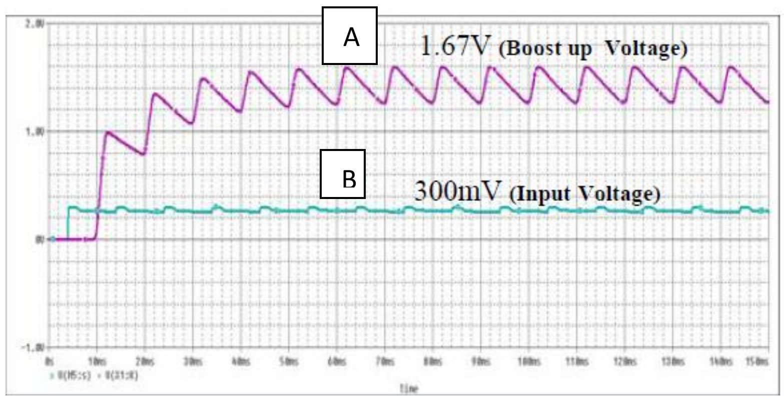


Figure 3.4 Voltage Output of the DC-DC Converter (Step-UP).

The overall circuit efficiency is about 80%, following the simulation results.

Chapter 4: Implementation of Charging Module

A prototype wearable device designed and made for charging handheld devices, smart watches, phones, video game devices, etc, using electricity harvested from body heat using a low voltage thermoelectric generator.

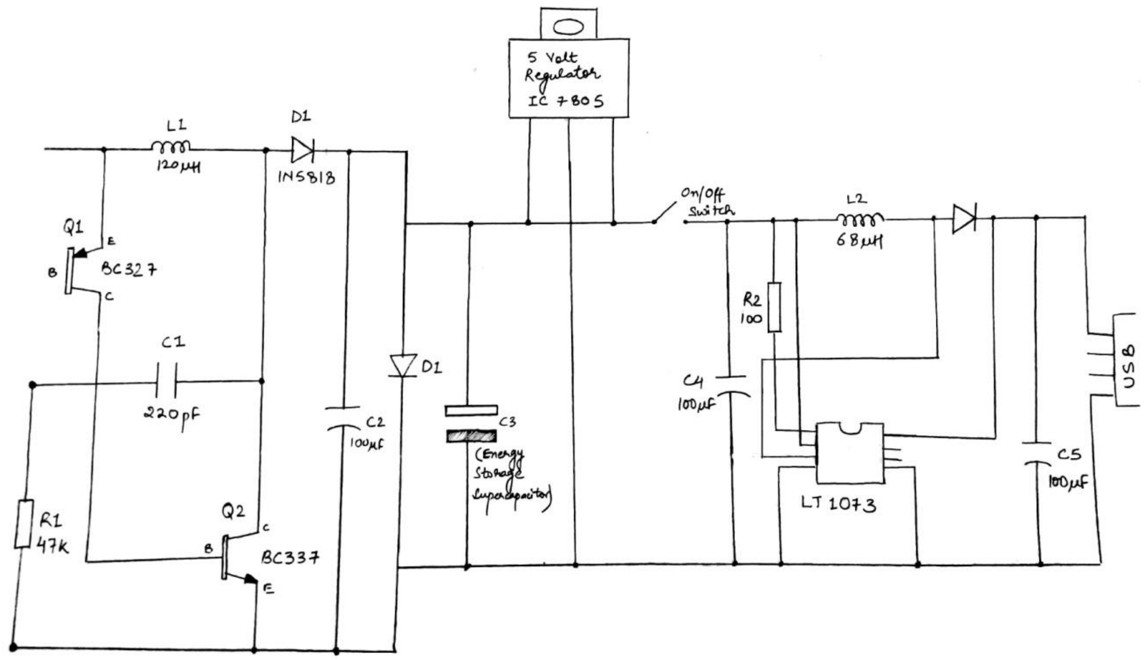


Figure 4.1 Voltage Booster Circuit

Thermoelectricity produced from bismuth-telluride peltier elements by the Seebeck effect produces a low voltage and a more or less stable current when a constant temperature differential is created across the element. This can be accomplished by having a constant heat source and a constant heat sink, i.e. a cooling apparatus. The low voltage can be boosted using a standard low voltage boosting circuit which boosts the voltage from milli-volts to around 5V.

Such circuits have become more and more widespread as the field of energy harvesting grows, with thermoelectric flashlights being developed for mass production for sale to the public in the near future as people become more aware of renewable energy and as the renewable energy economy grows which will only increase the demand for such devices in the electronics industry.

Making thermoelectric energy harvesting devices that charge devices with a more intensive energy demand than LEDs is a bigger challenge and requires the device to have more elements and a faster yet more continuous method of harvesting the energy as the temperature differential is diminished as is the case for devices which are cooled by the air as the cooler side eventually heats up itself.

As the user moves around, the change in the external environment will affect the amount of power produced. For example, walking or running outside with the device exposed will not only allow more heat to be harvested as the body expels waste heat but the movement will move air across the coolers which will sustain the temperature differential. In cold weather and environments the device will also work very efficiently. In warm weather or if the user is indoors and not moving the amount of power produced will be reduced. Hence the power harvested is intermittent.

Ultra-capacitors/Super-capacitors are therefore useful for storing the intermittent periods of a strong temperature differential forming across the elements as a voltage which is contained in the capacitor bank as long as the circuit is not switched. When power is required, the circuit is switched on and the capacitors are drained. The circuit is then switched off to let the charge rebuild again.

In this demonstration, the power is transferred periodically into a commercially available power bank which stores the electricity for further use in the range of portable rechargeable devices that people have grown accustomed to in the modern age. As progress continues, devices like this will be improved upon more and more until they are eventually commercially available and affordable for people to incorporate such technology into wearable devices and clothing to have more sustainable sources of energy to power potable technologies on the go without having to depend on power outlets.

In the future, it is hoped, that technology such as this will help replace our dependence on inefficient and environmentally unfriendly batteries and an over-reliance on using power outlets to charge small devices which is itself wasteful due to the waste heat created by transformation of current from AC to DC.

4.1 Description of the components in the prototype:

4.1.1 Super Capacitor

A **super-capacitor** (**SC**) (sometimes **ultra-capacitor**, formerly **electric double-layer capacitor (EDLC)**) is a high-capacity electrochemical capacitor with capacitance values up to 10,000 farads at 1.2 volt that bridge the gap between electrolytic capacitors and rechargeable batteries. They typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries. They are however 10 times larger than conventional batteries for a given charge.

Super-capacitors are used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage or burst-mode power delivery. Smaller units are used as memory backup for static random-access memory (SRAM).

Super-capacitors do not have a conventional solid dielectric. They use electrostatic double-layer capacitance or electrochemical pseudo capacitance or a combination of both instead:

- Electrostatic double-layer capacitors use carbon electrodes or derivatives with much higher electrostatic double-layer capacitance than electrochemical pseudo capacitance, achieving separation of charge in a Helmholtz double layer at the interface between the surface of a conductive electrode and an electrolyte. The separation of charge is of the order of a few Ǎ (0.3–0.8 nm), much smaller than in a conventional capacitor.

- Electrochemical pseudo capacitors use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudo capacitance. Pseudo capacitance achieved by Faradaic electron charge-transfer with redox reactions, intercalation or electrosorption.
- Hybrid capacitors, such as the lithium-ion capacitor, use electrodes with differing characteristics: one exhibiting mostly electrostatic capacitance and the other mostly electrochemical capacitance.

The electrolyte forms a conductive connection between the two electrodes which distinguishes them from electrolytic capacitors where the electrolyte is the second electrode (the cathode). Super-capacitors are polarized by design with asymmetric electrodes, or, for symmetric electrodes, by a potential applied during manufacture.

4.1.2 Voltage Regulator

Voltage Regulator is one of the most important and commonly used electrical components. Voltage Regulators are responsible for maintaining a steady voltage across an Electronic system. Voltage fluctuations may result in undesirable effect on an electronic system, so to maintaining a steady constant voltage is necessary according to the voltage requirement of a system.

IC 7805 is a 5V Voltage Regulator that restricts the voltage output to 5V and draws 5V regulated power supply. It comes with provision to add heat sink.

The maximum value for input to the voltage regulator is 35V. It can provide a constant steady voltage flow of 5V for higher voltage input till the threshold limit of 35V. If the voltage is near to 7.5V then it does not produce any heat and hence no need for heat sink. If the voltage input is more, then excess electricity is liberated as heat from 7805.

It regulates a steady output of 5V if the input voltage is in rage of 7.2V to 35V. Hence to avoid power loss try to maintain the input to 7.2V. In some circuitry voltage fluctuation is fatal (for e.g. Microcontroller), for such situation to ensure constant voltage **IC 7805 Voltage Regulator** is used.

IC 7805 is a series of 78XX voltage regulators. It's a standard, from the name the last two digits 05 denotes the amount of voltage that it regulates. Hence a 7805 would regulate 5V and 7806 would regulate 6V and so on.[7]

4.1.3 LT1073

The LT1073 is a versatile micro power DC/DC converter. The device requires only three external components to deliver a fixed output of 5V or 12V. The very low minimum supply voltage of 1V allows the use of the LT1073 in applications where the primary power source is a single cell. An on-chip auxiliary gain block can function as a low battery detector or linear post-regulator.

The LT1073 is gated oscillator switcher. This type architecture as very low supply current because the switch is cycled only when the feedback pin voltage drops below the reference voltage. Circuit operation can best be understood by referring to the LT1073 Block Diagram. ComparatorA1 compares the FB pin voltage with the 212mVreference signal. When FB drops below 212mV, A1 switches on the 19 kHz oscillator. The driver amplifier boosts the signal level to drive the output NPN power switch Q1. An adaptive base drive circuit senses switch current and provides just enough base drive to ensure switch saturation without overdriving the switch, resulting in higher efficiency. The switch cycling action raises the output voltage and FB pin voltage. When the FB voltage is sufficient to trip A1, the oscillator is gated off. A small amount of hysteresis built into A1 ensures loop stability without external frequency compensation. When the comparator is low the oscillator and all high current circuitry is turned off, lowering device quiescent current to just 95µA for the reference, A1 and A2.

The oscillator is set internally for 38µs ON time and 15µsOFF time, optimizing the device for step-up circuits where V_{OUT} =3V_{IN} (approx), e.g., 1.5*V* to 5*V*. Other step-up ratios as well as step-down (buck) converters are possible at slight losses in maximum achievable power output. A_2 is a versatile gain block that can serve as a low-battery detector, a linear post-regulator, or drive an under voltage lockout circuit. The negative input of A_2 is internally connected to the 212mV reference. An external resistor divider from V_{IN} to GND provides the trip point for A_2. The A_O output can sink 100µA (use a 56K resistor pull-up to 5V). This line can signal a microcontroller that the battery voltage has dropped below the preset level.

A resistor connected between the I_{LIM} pin and V_{IN} adjusts maximum switch current. When the switch current exceeds the set value, the switch is turned off. This feature is especially useful when small inductance values are used with high input voltages. If the internal current limit of 1.5A is desired, I_{LIM} should be tied directly to V_{IN}. Propagation delay through the current-limit circuitry is about 2µs.In step-up mode, SW_2 is connected to ground and $SW1$drives the inductor. In step-down mode, S_{W1} is connected to V_{IN} and SW_2 drives the inductor. Output voltage is set by the following equation in either step-up or step down modes where R_1 is connected from F_B to GND and R_2 is connected from V_{OUT} to F_B.

$$V_{out} = (212mV)\left(\frac{R_2}{R_1} + 1\right) \tag{4.1}$$

Inductor Selection: A DC/DC converter operates by storing energy as magnetic flux, in an inductor core and then switching this energy into the load. Since it is flux, not charge, that is stored, the output voltage can be higher, lower, or opposite in polarity to the input voltage by choosing an appropriate switching topology. To operate as an efficient energy transfer element, the inductor must fulfill three requirements. First, the inductance must be low enough for the inductor to store adequate energy under the worst-case condition of minimum input voltage and switch ON time. The inductance must also be high enough so that maximum current ratings of the LT1073 and inductor are not exceeded at the other worst-case condition of maximum input voltage and ON time. Additionally, the inductor core must be able to store the required flux, i.e., it must not saturate. At power levels generally encountered withLT1073-based designs, small axial-lead units with saturation current ratings in the 300mA to 1A range(depending on application) are adequate. Lastly, the inductor must have sufficiently low DC resistance so that excessive power is not lost as heat in the windings. An additional consideration is electro-magnetic interference (EMI). Toroid and pot core type inductors are recommended in applications where EMI must be kept to a minimum; for example, where there are sensitive analog circuitry or transducers nearby. Rod core types are a less expensive choice where EMI is not a problem. Specifying a proper inductor for an application requires first establishing minimum and maximum input voltage, output voltage and output current. In a step-up converter, the inductive events add to the input voltage to produce the output voltage.

Capacitor Selection: Selecting the right output capacitor is almost as important as selecting the right inductor. A poor choice for a filter capacitor can result in poor efficiency and/or high output ripple. Ordinary aluminum electrolytics, while inexpensive and readily available, may have unacceptably poor equivalent series resistance (ESR) and ESL (inductance). There are low-ESR aluminum capacitors on the market specifically designed for switch-mode DC/DC converters which work much better than general purpose units. Tantalum capacitors provide still better performance at more expense. In very low power applications where every microampere is important, leakage current of the capacitor must be considered. If the load is also in the microampere range, leaky capacitors will noticeably decrease efficiency. In this type application tantalum capacitors are the best choice, with typical leakage currents in the 1μA to 5μA range.

Diode Selection: Speed, forward drop and leakage current are the three main considerations in selecting a catch diode for LT1073converters. “General-purpose” rectifiers such as the1N4001 are unsuitable for use in any switching regulator application. Although they are rated at 1A, the switching time of a 1N4001 is in the 10μs to 50μs range. At best, efficiency will be severely compromised when these diodes are used and at worst, the circuit may not work at all. Most LT1073 circuits will be well served by a 1N5818Schottky diode. The combination of 500mV forward drop at 1A current, fast turn-on and turn-off time and 4μA to10μA leakage current fit nicely with LT1073 requirements. At peak switch currents of 100mA or less, a 1N4148 signal diode may be used. This diode has leakage current in the1nA to 5nA range at 25ºC and lower cost than a 1N5818.In situations where the load is intermittent and the LT1073is idling most of the time, battery life can sometimes be extended by using a silicon diode such as the 1N4933, which can handle 1A but has leakage current of less than1µA. Efficiency will decrease somewhat compared to a1N5818 while delivering power, but the lower idle current may be more important.

Step-Up (Boost Mode) Operation: A step-up DC/DC converter delivers an output voltage higher than the input voltage. Step-up converters are not short-circuit protected since there is a DC path from input to output. The usual step-up configuration for the LT1073 is shown in Figure 5.3. The LT1073 first pulls SW1 low causing VIN VCESAT to appear across L1. A current then builds up in L1.At the end of the switch ON time the current in L1 is:

$$i_{PEAK} = \frac{V_{IN}}{L} t_{ON} \tag{4.2}$$

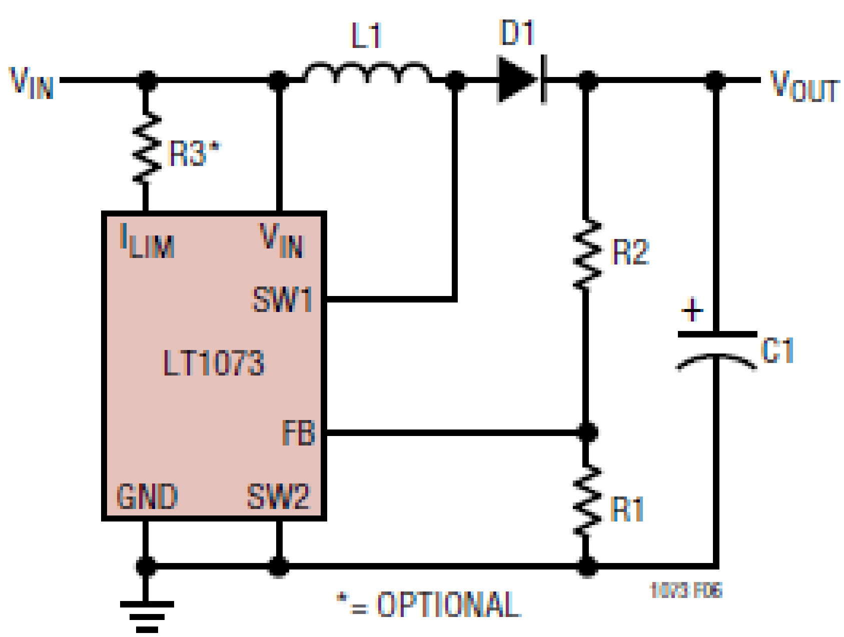


Figure 4.3. Step-Up Mode Configuration of LT1073 [11]

Immediately after switch turn-off, the SW1 voltage pin starts to rise because current cannot instantaneously stop flowing in L1. When the voltage reaches VOUT + VD, the inductor current flows through D1 into C1, increasing VOUT. This action is repeated as needed by the LT1073 to keep VFB at the internal reference voltage of 212mV. R1and R2 set the output voltage according to the equation 4.1. [10]

4.2 WORKING

In order to get voltage higher than 6mV we have used 4 TEG modules in series. The output from this combination is fed into the micro voltage booster circuit, from where the boosted up voltage is fed into a power bank for storage so that the power can be further used.

In order to hold the four TEGs together, they are secured onto a wrist band as shown.

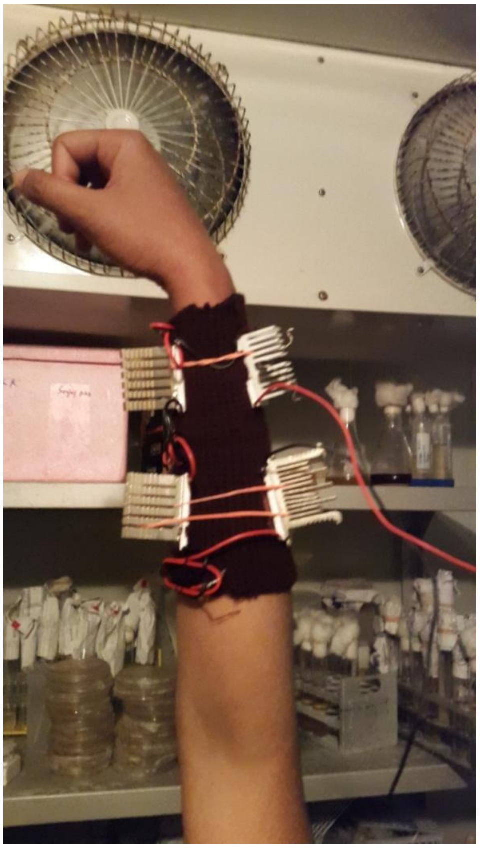


Figure 4.4 Four TEGs secured onto a wrist band.

The voltage output obtained from the combination of four TEGs in series.

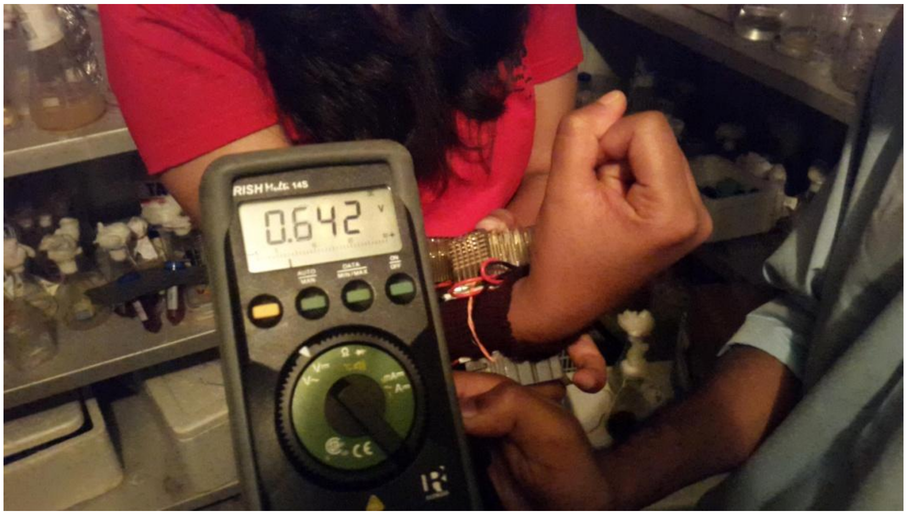


Figure 4.5 Measuring voltages from the combination of four TEGs.

We also observed that the results obtained varied from person to person and also depended on the area of the body where the TEGs were applied.

Table 4.1 Results obtained from 2, 3 and 4 TEGs in series at room temperature.

	2 in series Voltage (mV)	**3 in series Voltage (mV)**	**4 in series Voltage (mV)**
Person 1	266	342	499
Person 2	274	381	500
Person 3	350	428	521

Table 4.2 Results obtained from 2,3 and 4 TEGs in series in the cold room.

	2 in series (mV)	**3 in series (mV)**	**4 in series (mV)**
Person 1	421	589	649
Person 2	498	668	754
Person 3	465	688	802

Table 4.3 Results obtained from TEG at various points of the body.

	Palm (mV)	Wrist (mV)	Forearm (mV)	Elbow (mV)	Arm (mV)
Person 1	124	143	151	162	172
Person 2	102	123	143	150	165
Person 3	117	135	154	167	182

In general we can see that the voltage increased as we moved from the palm towards the arm.

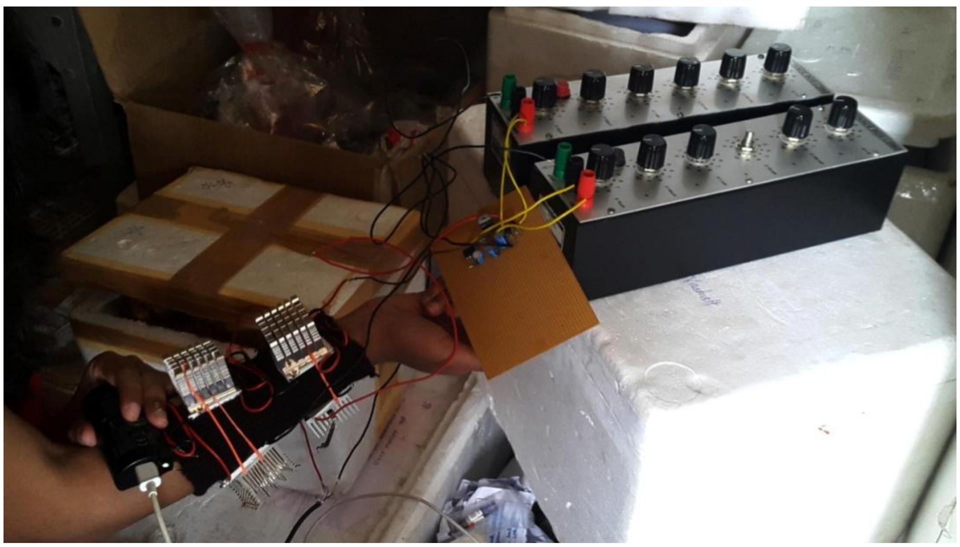


Figure 4.6 TEG Band coupled with the booster circuit charging the power bank.

Results: We performed our experiment in the cold room where the temperature was very low, around 2-3ºC. We require low temperature so that the temperature gradient is maintained. A power bank was connected to the voltage booster circuit which was successfully charged by the setup.

Chapter 5: Conclusion and future work

The TEG based energy harvesting circuit presents an easy and efficient method of generating electricity from the human body heat. The source of powering the device is inexhaustible and the energy harvested from this circuit will be helpful in supplementing the increasing demand for electricity.

In the future, we hope that technology such as this will help replace our dependence on inefficient and environmentally unfriendly batteries and an over-reliance on using power outlets to charge small devices which is itself wasteful due to the waste heat created by transformation of current from AC to DC.

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