ABSTRACT

RAVINDRAN, PATTABHIRAMAN. Harvesting Thermal Energy to Power Agricultural Sensors. (Under the direction of Prof. Paul D. Franzon.)

In this thesis, a prototype of a thermal energy-harvesting device is built. Using the thermal energy from the earth, an agricultural sensor such as a soil-NPK indicator or a soil-moisture indicator is designed to be powered. The thermal energy is converted to electrical energy (potential difference) using a Peltier device or a Thermo-electric generator (TEG). A temperature difference sufficient to produce a voltage of 30-35 mV is required between the sides of the TEG. This is obtained by keeping one plate of the Peltier device attached to a thermal conductor exposed to the environment, and the other plate attached to a thermal conductor that goes into the ground. Copper rod with varying insulation and aluminum plates are analyzed to be used as the thermal conductors, for this purpose. The open circuit DC voltage output of 35-40 mV from the Peltier device which drops to 20-25 mV on load, is stepped-up to 5 V by a power manager consisting of DC-DC step-up converter, and stored in a capacitor. The charged capacitor powers the sensor when requested.

The device will work autonomously without the need for batteries. This removes battery costs and the need for battery replacements, apart from negating concerns of pollution caused by battery disposal.

Temperature difference as small as 5°C, between ambient temperature and ground temperature, is harvested using Peltier device and power manager to charge a capacitor to 5 V. This can be used to power a sensor at intervals of less than four minutes provided the temperature difference is maintained. Due to the slow change of temperature of the soil, the sensor can be powered using the current technique for the most part of the year.

Implementation choices that are more efficient to maintain temperature difference across the plates of the Peltier device are described. Feasibility of trickle charging, which is another application of an energy harvesting device, is also discussed.

Harvesting Thermal Energy to Power Agricultural Sensors

by
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DEDICATION

This thesis is dedicated to the sun of the solar system!

BIOGRAPHY

I was born in Chennai, India. I completed Bachelor of Engineering in Electronics and Communication Engineering, and worked for a couple of years in software engineering. I came to North Carolina State University in fall 2009 to do Masters in Computer Engineering, focusing on Digital VLSI Design. I started my Master's thesis in energy harvesting during the summer of 2010.

I am a passionate bird-watcher, and love playing a number of sports. My new interests are philosophy, psychology and photography.

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I thank Mr. Sai Ramana Shanker for his contributions during fall 2010, while he was a part of this project, and my friends at NCSU for making my life here, a wonderful one. I particularly thank Mr. Steve Edwards, who was kind to take me out for a number of birding visits, and I immensely thank my childhood friends who have guided me in a number of ways.

I am grateful to my parents for their encouragement and advice, apart from funding my education. Separating after living with them for close to a quarter of a century, has brought out their importance even more!

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LIST OF ABBREVIATIONS, SYMBOLS AND FORMULAE

μA	Mirco-Amperes
μF	Micro-Farads
μW	Micro-Watts
ΔT	Temperature Difference
C	Celsius
CAD	Computer Aided Design
cm	Centi-metre
CPU	Central Processing Unit
CO_2	Carbon di-oxide
DC	Direct current
DFN	Dual Flat No-lead
EAGLE	Easily Applicable Graphical Layout Editor
EMF	Electromotive force
F	Farad
J	Joules
K	Kelvin
Li	Lithium
LT	Linear Technology
m	Metre
mA	Milli-Amperes

MEMS	Micro electrical Mechanical System
mV	Milli-Volts
mW	Milli-Watts
NC	North Carolina
nF	Nano-Farad
NH_4^+	Ammonium
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
NO_3^-	Nitrate
NPK	Nitrogen-Phosphorous-Potassium
OCV	Open Circuit Voltage
PCB	Printed circuit board
pF	Pico-Farads
PGD	Power Good
PVC	Poly Vinyl Chloride
RF	Radio Frequency
S	Seconds
SLA	Sealable Lead Acid
SSOP	Shrink Small-Outline Package
TDR	Time-domain reflectometer
TEG	Thermo-electric generator
V	Voltage

VS Versus

W Watts

XLP eXtreme Low Power

XRF X-ray fluorescence

CHAPTER 1

Introduction

1.1 Motivation

Energy harvesting provides an alternative to the use of batteries, which results in cutting battery replacement efforts and costs. This is particularly useful in cases where it is inconvenient to replace batteries, like in undersea or at towers. Battery disposal causes pollution problems, as a number of heavy metals are used. This is never a concern for energy harvesting devices.

When an energy harvesting mechanism is used in a device with battery, the battery can be trickle charged when not in use. One can put the amount of charge that is consumed by the sensor, back into the battery. This prolongs the use of a sensor without battery replacement. In case of solar energy harvesting, batteries are charged up for later use.

Agricultural sensors are good candidates for being powered by energy harvesting mechanisms. Sensors are used for measuring moisture or pH content of the soil, and are not used continuously. Once the values are read, the sensors are powered off. After addition of moisture or pH changing material to the soil, the sensors are powered on to note the new readings. During the phases the sensors are not in use, a mechanism can be used to accumulate charge on a capacitor. The voltage built up across the capacitor can be used to power the sensors when requested.

LTC3108 chip from Linear Technologies is a power manager that helps store electrical energy. A 1:100 transformer and capacitors along with the chip can be integrated together to form a DC-DC step-up converter. This circuit can utilize a small input voltage of 20 mV or above, to charge a capacitor to 5 V.

Thermo-electric generators are transducers that convert thermal energy to electrical energy. An input voltage of 20 mV can be obtained from a temperature difference as low as 2 or 3 K across the sides of the Thermo-electric generator. By integrating the transducer, power manager circuit, and the sensor, a model that is battery-less can be built.

1.2 Goal of the Project

A number of researchers have proposed materials and mechanisms to harvest energy. A number of other researchers have proposed devices that have transducers and circuits to manage power, to be used in energy harvesting devices. Some have successfully demonstrated operation in laboratory under favorable conditions. There have also been failures that go undocumented. Electrical engineers are researching on low power sensors, which can be used for energy harvesting or otherwise. Energy harvesting typically is used to power a sensor node, and not the whole sensor. Low power micro-controllers that draw a few μA of current are the general candidates being researched for being powered. This project is aimed at integrating transducers, power manager circuits, and agricultural sensors available in the market, to determine if energy harvesting mechanism can be used for powering agricultural sensors. The focus is on powering the entire sensor with ambient energy, and not just a sensor node.

This thesis studies the feasibility of harvesting thermal energy available as temperature difference between the environment and under-ground. Using a Thermo-electric generator and a power manager, the electrical energy converted from thermal energy can be used for the purposes of powering a sensor or trickle charging a rechargeable battery. This project builds such a model, and identifies the constraints under which such a model works, and looks at the factors that would facilitate more efficient operation.

The thesis also talks about the battery life reduction that one needs to have in mind before using an energy harvesting device for trickle charging batteries.

1.3 Overview of the Following Chapters

Chapter 2 explains about energy harvesting in general, and the different types of energy harvesting under research, including thermal energy harvesting, which is the focus of this thesis. Chapter 3 starts off to give an overview of thermocouples and Thermo-electric generators or Peltier devices. The chapter explains the mechanical structures that were implemented to help maintain the temperature difference between the plates of a Peltier device so as to produce a voltage large enough to activate the DC-DC converter. It goes on to discuss about the thermal calculations needed, and concludes with descriptions of thermal conducting structures for mobile and fixed sensor applications. Chapter 4 explains the electronic circuit that functions as a power manager. A chip along with a transformer and a seven capacitors, steps up DC voltage, and stores energy in a capacitor. The capacitor is the source of power to the sensor. Chapter 5 covers the applications of the energy harvesting device. It explains the agricultural sensors that were analyzed and used for being powered by the harvested energy. It discuses about the various sensors available at present. It concludes with a discussion on the factors one needs to consider while designing an energy harvesting device with an intention to trickle charge a rechargeable battery. In Chapter 6, the methodology and results of testing at the laboratory as well as the field where the sensor is designed to be used, are discussed. The second part of the chapter discusses the power or energy values as the case may be, at each component of the power harvesting system. Conclusions drawn and the scope for future work are discussed in Chapter 7.

CHAPTER 2

Energy Harvesting

2.1 Overview of Energy Harvesting

Scavenging ambient sources of energy like environmental vibration, heat, light, and electro-magnetic energy to power electronic devices (usually sensors) is called energy harvesting or energy scavenging. Energy harvesting is seen as an alternative for use of batteries in low-power sensors that are both wireless and non-wireless. They are typically considered to power low-power wireless sensor nodes. The sensors could be in a remote location like in under-sea, or could be in a situation where the plant needs to shut down for battery replacement due to hazardous conditions. The other use is to charge up rechargeable batteries for later use. In cases of solar energy harvesters, a bunch of batteries are kept, and trickle charged by the energy harvesting mechanism. This will help in supplying power during non-availability of sun-light. Trickle charging will also prolong the usage of the sensor, before the next cycle of recharging or battery replacement.

Using alternative energy to power sensors is gaining popularity, as non-renewable sources of energy will not last forever considering their increasing usage and finite availability. CO_2 emission by fossil fuels, such as petroleum products causes global warming. Nuclear energy generation has safety concerns due to radiation leaks that are caused by damages to the reactors [1]. This project studies the feasibility of using an alternative source of energy, which is renewable or sustainable, and clean, for powering agricultural sensors. The thermal energy from the earth is a source that can be used for this purpose.

Energy harvesting devices are characterized by power density. The idea is to store charge in a capacitor, which will deliver a current to the sensor node until the voltage falls below a level. This level will be dependent on the voltage levels a sensor can tolerate. The supply is cut until the capacitor charges up to a sufficient voltage to power the sensor once again. The energy stored in the capacitor and the time taken for storing it, determine the power capability of the device. Bigger devices harvest more energy. Hence area or volume, as the case may be, is used along with power to give the power density.

Reduction of device area is another motive for energy harvesting. With circuit area becoming smaller, the batteries are occupying relatively more area. Replacement of battery with a smaller energy harvesting device is being considered for reducing the overall device size. However, this is not the motivation for the current thesis. Smaller devices for energy harvesting will tend to give lesser power due to reduced area for extracting ambient energy. This makes the motive harder to achieve.

A number of factors need to be taken into account while designing an energy harvesting device.

1. In the place where the sensor is designed to be used, the ambient energy that is designed to be harvested should be available for a good period of time to ensure really battery-less operation periods. If not, the success at the laboratory will not be reproduced in the outside world.
2. The device needs to have a storage component, namely a capacitor or a super-capacitor. Larger the capacitor, more the charge that can be stored for the same voltage, but higher the leakage current. Larger Capacitors also take more time to charge up to the same voltage.
3. The sensor must consume only that much energy which can be harvested into the capacitor, before the next point of operation. If not, a battery is a must.
4. In the cases where use of battery is imperative, a rechargeable battery can be charged if the ambient energy is high enough to be harvestable. The operation of the sensor without battery replacement can then be prolonged.
5. The sensor must be designed such that it does not indicate a wrong value due to different values of supply voltages. This is true in the case of meters using current

flow to indicate values. Care must be taken in the design to ensure that the sensor starts to indicate or transmit, only when the voltage across the capacitor is under regulation.

[29] gives an overview of the energy harvesting systems. [30] looks at projects trying to harvest energy from different sources to power sensor nodes.

EnOcean (http://www.enocean.com/) is aiming to provide a complete integrated chip that has a transducer, power manager, and a wireless sensor. For a thermal energy harvesting chip, heat from machinery and human body is proposed.

Tables 2.1 and 2.2 give the stages of research going on in the different types of energy harvesting, and predicts the progress into the future.

Table 2.1: Levels of progress in a prototype development

Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in a operational environment
8	Actual system completed and 'flight qualified' through test and demonstration
9	Actual system 'flight proven' through successful mission operations

Source:[1]

Table 2.2: Projected progress of each type of energy harvesting

	Energy and conversion mechanism	2008	2013	2018	2023
Macro systems (cm^3 level)	Piezoelectric (strain)	9	9	9	9
	Electrostatic (vibration)	6	7	8	9
	Electromagnetic (vibration)	8	9	9	9
	Thermoelectric	7	8	8	9
	Inductive RF	5	6	8	9
	Solar cells (Si, thin film)	8	9	9	9
Micro systems (mm^3 level)	Piezoelectric thin film (strain)	4	5	5	6
	Electrostatic (vibration)	3	4	5	6
	Electromagnetic (vibration)	5	6	7	8
	Thermoelectric	6	7	7	8
	Inductive RF	4	5	6	8
	Solar cells (plastic)	4	5	7	8

Source: [1]

The volumes represent the size of the energy harvesting mechanism. A smaller sized device is capable of harvesting lesser energy than a larger one. For example, a smaller TEG would produce a lower voltage across its terminals, compared to a bigger one. This presents more challenges for smaller energy harvesting devices. One is the improved efficiency required by the transducer, and the second is the need for an even lower power sensor nodes.

Some of the main sources of energy that can be harvested to power electronic devices are mechanical energy, thermal energy, light energy, and RF energy. They are briefly described below.

2.2 Mechanical Energy Harvesting

Some of the ways mechanical energy harvesting can be done is as follows:

1. Using peizo-electric material that produces electricity based on stress or vibration
2. Variable capacitors that dump charge based on mechanical motion. The distance between the plates change due to vibration or motion.
3. Motion under a magnetic field
4. Kinetic energy of spring, wind, or water

Relatively more research in energy harvesting is in using peizo-electric methods. Utilization of piezoelectric effect to power autonomous sensors is theoretically simulated in [2], and needs to be prototyped and tested. [3] proposes to harvest mechanical motion to charge a Li-ion battery. Mechanical motion changes the distance between the plates of a capacitor. The change that goes out is used to charge the battery. In [4], possibility of using ambient vibration energy to power digital systems is studied. A chip was also designed and tested to demonstrate the feasibility of the same. [5] talks about a MEMS-based electromagnetic vibration-to-electrical power generator that can harvest energy from low-frequency external vibrations. A MEMS-based variable capacitor can be used to convert vibration to electrical energy for the purpose of powering low-power electronics [6]. [8] points to research happening in the field of harvesting ambient vibration using peizo-electric material.

Harvesting of wind-energy using wind-mills and hydro-energy from water-flow using turbines are proven to be successful, and both are used commercially. The former can be used in open-spaces where lot of wind is available. The latter can be used in dams as the water hits the bottom with great force. The potential energy of water is converted into kinetic energy (both are components of mechanical energy), which is ultimately converted into electrical energy. Both are for high-voltage electric energy production.

For low power wind-energy harvesting applications, the movement of a magnet is used to get electrical energy using aerodynamic instability called “wake galloping”. Using wind-speeds of 1.8 to 5.6 m/s, 0.3 to 1.13 W are proposed to be generated [9]. In [10], wind energy is used to rotate the shaft of an anemometer that is connected to an alternator, which is a device that converts mechanical energy into electrical energy. With little impact on anemometer accuracy, the electrical energy is stored in a battery by trickle charging after sending through a buck-boost converter.

Energy from human motion is also being researched for powering electronic devices. Movement of arms or legs, and temperature gradient between environment and human body are trying to be harvested [1].

2.3 Light Energy Harvesting

Using photovoltaic cells or solar cells, sun light can be harvested to power electrical devices. Usage of this is documented, and is used where sun light is plentiful.

Solar energy is shown to be successful harvestable in [11]. A low power CMOS sensor with the capability to harvest light energy using photo-diodes is proposed in [12]. Solar energy is harvested to power a wireless sensor node in [13], where there are three sources of power to the sensor. One is the solar boards which convert ambient light energy into electrical energy. The second is a super-capacitor which is trickle charged using the solar cells. The third is an emergency power supply consisting of Li-ion batteries. [14] harvests indoor light energy using a photovoltaic cell which charges a rechargeable battery, and powers an ultra-low power wireless sensor node, which takes in only 2.5 µA. In [33], a DC-DC step up converter is used in the lab to harvest light energy using a solar cell. This device successfully powers a sensor node when light is shined on top of the solar cell. The power manager converts 40 mV to 4.1 V.

XLP 16-bit Energy harvesting development board (DV164133) from Microchip is a kit that helps prototyping low power sensors. It harvests solar energy using Cymbet's EVAL-08 Solar Energy harvester. Energy is stored into Cymber EnerChipTM thin-film rechargeable energy storage devices [40].

2.4 Thermal Energy Harvesting

Some of the sources of heat are as follows:

1. Friction produced by motion
2. Electrical current through a resistor
3. Heater/Air-conditioner, or radiators
4. Earth (underground)
5. Flame
6. Steam
7. Hot/cold liquids such as coolants   [source: micro°pelt]

There are a number of challenges in using temperature difference to power sensors. One is the low efficiency of energy conversion. Carnot efficiency is given by the formula $\Delta T/Th$, where ΔT is temperature difference trying to be harvested, and Th is the higher temperature of the two. All temperatures are in Kelvin units. When the higher temperature is 35°C, and the lower temperature is 20°C, Carnot efficiency comes to about 5 %. The second challenge is the less availability of a high enough ambient temperature difference to harvest.

Even in cases they are available, it is a challenge to maintain the temperature difference across the plates of a TEG.

A TEG is simple, easy to use, and has no moving parts, which prolongs its life. It is the main source, if not the only one, for converting temperature differences into electrical energy. Research is going on in the development of new materials for TEG for better efficiency [15]. More efficient devices would be particularly useful for energy harvesting devices where one gets a temperature difference of only a few Kelvin to harvest.

A prototype with TEG and a DC-DC converter is tested with a heat source that emulated the heat from a radiator in [16]. Mechanisms like these would work relatively easily since there is a good temperature source available to harvest using TEGs. The transducer (TEG) and the power manager circuitry is characterized in [17], and is modeled and designed. With this, one can simulate the behavior before constructing the model and trying out in the field. The feasibility of TEG for energy harvesting is studied in [18], where it shows good capability to activate DC-DC converters. Using a transmitter receiver pair, and thermal and solar energy harvesters, various performance parameters are studied in [19]. Thermic watch from Sikeo utilizes body heat to power a wrist watch and charge a Li-ion battery [20]. Laptop battery is shown to be charged using harvested energy in [21], by using a burner and a DC-DC converter. [7] gives an overview of potential applications of TEGs.

[22] deals with utilization of body heat. The temperature difference between the body and the environment produces a voltage across a TEG which is stepped-up using a DC-DC converter, and powers a voltage, current and temperature indicator. Any application that utilizes human body heat will work well as long as the outside temperature is much below the normal body temperature of 37°C. When the ambient temperature is close to that of the body's, the ability to harvest energy decreases. However, a person living in an air-conditioned room can utilize the huge temperature difference. Even during late fall and winter period at Raleigh, NC, it was seen that the temperature ranges from sub-zero to 15°C. Just touching a side of the TEG gives 80mV. This is sufficient for activating DC-DC converters.

Automotive TEGs (ATEG) can be used in internal combustible engine to utilize heat from engine or coolant. The efficiency is currently very low, and is hoped that material research will help in an improvement.

Geo-thermal energy is used in places with hot springs and volcanoes. The heat from the earth is collected using a fluid, which is then used to heat a liquid to produce steam that rotates a turbine. This mechanical energy of the turbine is converted to electrical energy. A disadvantage is that we get green-house gases from under-ground which contributes to global warming. Another problem is that sometimes one has to dig deep into the earth for harvesting the heat underground.

Possible ways of using thermal energy harvesting is discussed in [23], and it was found that most methods do not yield enough energy.

Micro°pelt is building prototypes of energy harvesting devices using TEGs. They also have TEGs available for use in energy harvesting applications.

Generally, the source of energy available for harvesting in a commercial application is quite low. To deal with this, multiple types of energy harvesters can be combined to give a more steady power. Similar to [28], thermal energy and light energy are harvested using a TEG, solar cell, and a power manager circuit, and is prototyped in [31].

2.5 Electro-magnetic Energy Harvesting

There is research going on in harvesting electromagnetic waves, where RF sources can be converted to DC power. Laboratory testing using rectennas that convert microwave energy to DC electricity have yielded positive results. However, energy produced in the outside world is not high enough for powering electronic devices in most cases [1].

Solar energy cannot be harvested during the night, but TV broadcast signals are present for most periods if not all. Energy is harvested using a rectenna to charge a capacitor to 2.9 V, which powers a sensor node [24]. Ambient RF energy is harvested using rectennas near mobile phone base station in [25]. The maximum power obtained was 0.1 µW, which is claimed to be useful to power low-power wireless sensors or trickle charge a super-capacitor or a battery. RF energy from radio station is harvested, and stored in a capacitor to a voltage of 520 mV [26]. In [27], an output voltage of 72.5mV was obtained with a Schottky diode, and 428.3mV with LTC5535 rectifier, at a distance of 15 cm from the reference antenna.

In [28], both thermal energy and RF energy are harvested, sent through a DC-DC converter, and used to charge a battery. This technique has a higher probability of working when ambient conditions keep changing, as two sources are used. When a TV or Radio station stops transmission, RF energy sources are absent. However, a presence of a temperature gradient can be harvested using a TEG.

CHAPTER 3

Thermal to Electrical energy Conversion

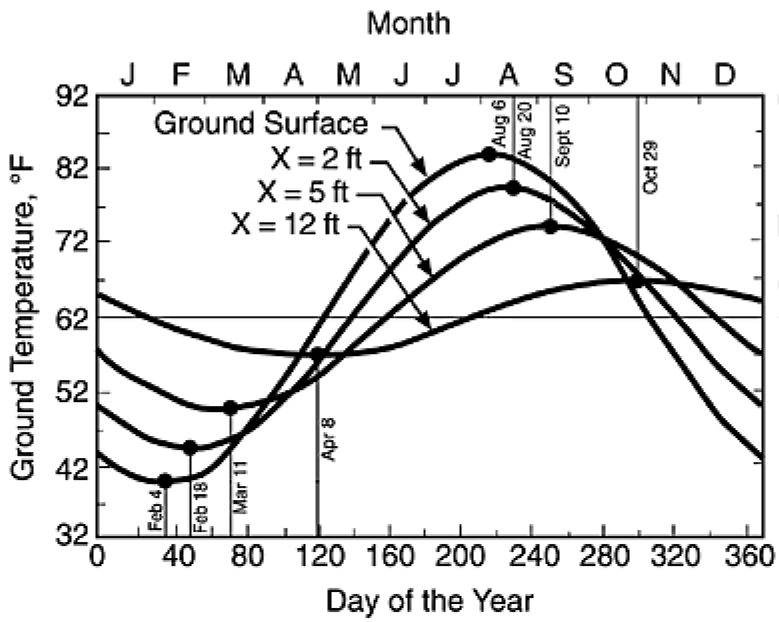
3.1 Temperature Sources

The source of energy that is utilized in this thesis is the temperature difference between the soil (under-ground) and the environment. The temperature of the environment varies during the day, and is generally at the highest point during the middle part of the day. Suppose the temperature under the surface of the soil is about 20°C, and the ambient temperature increases from 20°C in the morning to 30°C in the afternoon and then back to 20°C at dusk. The temperature under the ground remains more or less constant at 20°C. The device would work for parts of the day when the ambient temperature is at least 25°C. During times when temperature difference is insufficient, energy cannot be harvested. At these times, a battery is needed. The energy harvesting device can therefore be expected to function most of the time, except for certain times when temperature difference is insufficient.

The geography, in particular the atmosphere and the soil of the region need to be studied before deciding whether thermal energy harvesting using TEGs are feasible. This is similar to the cases where wind-mills are used to harvest the mechanical energy of the wind at windy open spaces only, solar panels are used to harvest light energy only in places with good sunshine or during times of good sunshine, and hydro energy (mechanical energy of water) is harvested at water-falls or dams. It was found that in Raleigh, NC, it is quite easy to get the required temperature difference, for most parts of the year.

The rate at which the soil loses or gains heat depends on the type of soil, the temperature changes that happen during the past, presence of rain, presence of shade and vegetation, and addition of water for irrigation among other factors. Based on experience it was found that the temperature depends more on the past history of temperatures, and drops down when there is rain.

Figure 3.1 shows the temperature variation at the surface of earth, and a few discreet distances below the surface at different times of the year. Plots such as these depend on many factors like the ones discussed earlier, and come with disclaimers. The data was taken from a place in Virginia, USA.



Source: [41]

Figure 3.1: Temperature Variation at different points below ground level at different days of the year

We see that as we go deeper, the temperature variation decreases. For example, at 12 feet, the temperature remains around 62°F for the most part of the year. It must be noted that the temperature at a given instance at and closer to the surface cannot be known beforehand due to dynamic variations of the ambient temperature and rain or addition of water. The plot is more of an average. The past history of temperatures is a good indication of these temperatures, and sticking a thermometer into the soil is an easy method to find the sub-soil temperature when desired.

The ambient temperature at a particular location is available at the respective regional meteorological offices. Minimum, maximum and average temperatures are available for each day of the year.

3.2 Thermo-electric Generators

When two different metals are connected in a loop, with different temperatures applied at the two junctions, a voltage is produced across the junctions. This is known as Seebeck effect, and is the principle of operation of a thermocouple. Just as batteries in series give an additive output voltage, thermocouples arranged in series give a higher output voltage. Such an arrangement of thermocouples is called a thermopile. The hot junctions are placed on one side, and the cold junctions are placed on the other side such that each side can be applied with a different set of temperatures. When such a device is used to produce voltage based on temperature difference, it is known as a Thermoelectric generator (TEG).

When current flows through a thermocouple, a temperature gradient forms across the metal junctions. One junction absorbs heat, while the other generates heat. This is known as Peltier effect, and is the concept used in thermo-electric cooling.

For this project, a TEG or a Peltier device was chosen to harvest the thermal energy from the earth using temperature difference, as it is the only convenient device for converting heat energy to electrical energy. TEGs are simple and easy to use. They have no moving parts, which makes their prolonged use possible. Researchers are trying to create more efficient TEGs, and the progress in this front is given in [32]. TEGs from two different manufactures were selected for this project, and both were similar in their voltages versus temperature difference characteristics.

TEGs were selected based on the Voltage versus ΔT graphs from the respective datasheets. V-Infinity, a division of CUI incorporated, provides efficient TEGs that match perfectly with the requirements. Micropelt's TEG showed good performance too. PT6.7.F2.3030.W6 and PT8.12.F2.4040.TA.W6 from Laird Technologies which are 3 cm by 3 cm and 4 cm by 4 cm respectively are good for the present application as well. They have electrical resistances of 1.22 Ω and 1.55 Ω respectively.

TEGs from V-Infinity were tested by keeping each sides of the device at known temperatures. The device was sandwiched between two conductors that were immersed in hot and cold water, with the initial temperature between the two being 35°C. The plots of the experiment conformed to the objective of giving out above 20 mV for a temperature difference of 10-20°C. It is to be noted that the temperature difference is not between the plates of the TEGs, but between the liquids. The heat is conducted to the TEG plates using aluminium plates. The temperature difference between the TEG's plates is thus lesser than that between the liquids. The plots in Figure 3.2 shows the voltages extracted from the TEGs for each size. Since TEGs have a series connection of thermocouples, bigger TEGs produce more voltage for the same temperature difference.

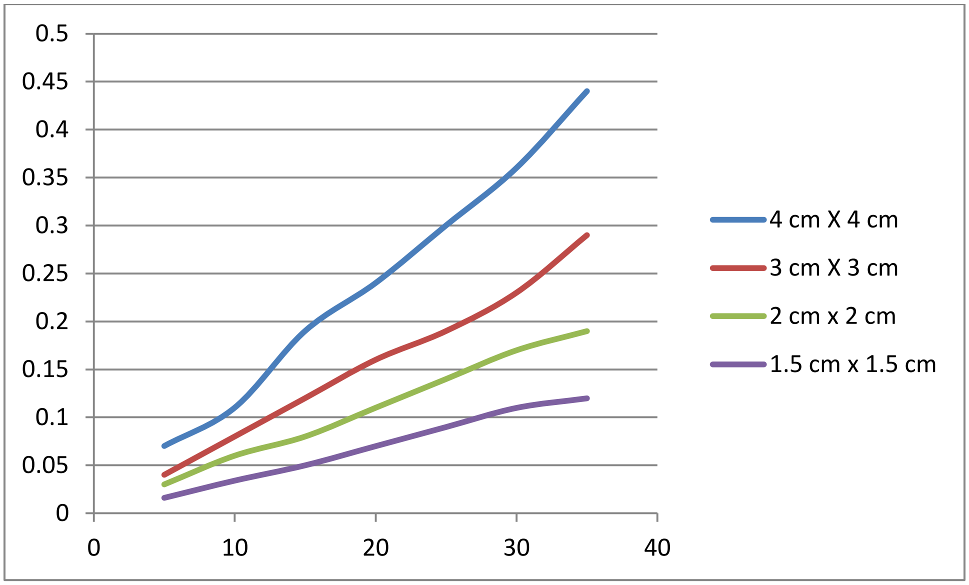


Figure 3.2: OCV vs ΔT for four TEGs between aluminium plates

The TEGs used in this project give enough output voltage to activate the DC-DC converter, when temperature difference of 2-3 K is applied across its plates. Never the less, higher the TEG gives for a given temperature difference, the better it is. [36] claims to be a good source for converting thermal energy to electrical energy. This TEG is not available commercially yet.

3.3 Structure of Thermal Conductors

For implementation in the field, a mechanism needs to maintain the necessary temperature difference between the plates of the TEG, so that a small voltage difference of at least 30 mV could be produced. The atmosphere acts as a source of a constant temperature for one side of the TEG. The other side needs to be such that we have a few (close to 5) Kelvin of temperature difference between the plates. The temperature under the ground is utilized for this. The hotness or chillness from the earth, the former during fall and winter, and the latter during spring and summer, can be used as a source for creating the temperature difference. A good thermal conductor needs to be used to transfer heat, and we have the choices of copper and aluminium. Gold and silver are expensive. Copper is a better conductor, and is generally used in CPUs for heat conduction, while aluminium is cheaper, and lighter in weight. Table 3.1 shows the thermal conductivities of the four metals at 25° [42].

Table 3.1: Thermal conductivities of good thermal conductors

Metal	Thermal Conductivity (W/m°C)
Silver	427
Copper	397
Gold	314
Aluminium	238

For testing the structure's feasibility, the first round of tests was conducted without any conducting material attached to the side of TEG exposed to the ambient temperature. This resulted in a small area of TEG not gaining enough heat transfer rate from or to the atmosphere. Having the heat source or sink is important due to the fact that the TEG also conducts heat from one side to the other. These experiments were conducted to determine the voltage that could be obtained, in order to choose the best structure. The final testing was included the heat source/sink. The next three sub-sections describe the first round of tests and the section 3.4 describes the complete structure.

3.3.1 Completely Insulated Copper Rod

The first mechanical structure tested is a three foot copper rod, enclosed completely in a (hollow) PVC pipe. PVC is a good thermal insulator. This structure makes sure that the copper rod does not get any temperature transferred from any part under the ground, except from the part of ground exposed to the cross-section of the rod. The inner diameter of the PVC pipe is $3/4^{th}$ of an inch, and the copper rod is 1/2 of an inch in diameter. The empty space between the rod and the pipe is filled with insulating foam.

Though air itself is a good thermal insulator, insulating foam is used. This is done so that we have even lesser heat transfer from the soil near the sides of the PVC into the rod. Apart from filling space, insulating foam sticks the rod to the pipe. After spraying foam, it is necessary to leave the pipe with the rod for drying, for a few hours. Once the rod is stuck, it is difficult to remove it from the pipe. The foam regains its position after mechanical jerks or pulls. The foam in itself is quite like glue. In order to remove the rod it is necessary to use acetone solution, and give a few hard jerks.

This pipe structure did not produce sufficient voltage even with close to 10°C between the underground and environment. Most of the time, there were just temperature differences of 4 to 7°C. In these conditions, this structure gave at most 1-2 mV of output from the TEG. Even after accounting for sufficient time to establish the necessary temperature gradient, the voltage levels obtained were of the order of a few milli-volts.

The temperature at the end of rod connected to the TEG should ideally be the under-ground temperature. In reality there would be heat transfers at all points. The rates of heat inflow and outflow will determine the steady state temperature.

An insulation tape is applied to the side of the TEG that is connected to the rod so that heat flow does not happen to or from the environment to the top part of the copper rod. A small air-gap at a single location will ruin the insulation from the environment. This is particularly possible at the places where the wires from the TEG come out. Despite the TEG having an insulating layer separating its plates, there is heat conduction through the device. These two factors determine the heat transfer rate between environment and the top part of the copper rod, which is connected to the TEG. As far as the ground temperature is concerned, there is just a small cross-section area (1 inch diameter) for the small temperature difference to be transferred across a long distance of three feet. This is particularly a problem when we are dealing with heat transfer of a few degrees Celsius of temperature difference. As heat is transferred, the temperature gradient decreases, which in turn decreases the rate of heat transfer. This determines the heat transfer rate between the copper rod and the under-ground. There is loss due to radiation and conduction from the sides of the copper rod since PVC is not a perfect insulator. The foam does not fill the space between the rod and PVC completely. The air, though an insulator, will also exhibit convectional movement within the pipe. A complete solution will involve solving complex differential equations in three dimensions. Suppose the ambient temperature is higher than the ground temperature near the bottom cross-section of the rod. The temperature at a point along the rod will keep increasing as we go from the bottom to the top.

3.3.2 Partially Insulated Copper Rod

A second structure with more area available for heat transfer from the ground is designed by cutting down the PVC insulation. It was observed that the temperature of the ground was pretty constant from about 5 cm and up to two feet below the ground. As a result of this, it is enough to insulate a portion at the top part of the rod. The length of PVC pipe used around the copper rod is reduced to about 20 cm. The voltage produced by the TEG for this arrangement came out to be 9-10 mV for a temperature difference of 11°C, which on time went down to 6 mV. The structure built is shown in Figure 3.3. Though this structure was better than the completely insulated structure, the voltage range is still not good enough to be harvested for lower voltage differences. A really large temperature difference during periods of above normal or below temperatures, or during season changes, will however, make this design feasible for use.

Ideally, this structure too should bring the cross-section of the rod connected to the TEG, to the temperature under the ground. The improvement is due to the fact that lesser insulation reduced the value of the effective length the heat needs to travel. This increased the heat transfer rate of the rod to carry the ground temperature to the TEG. A better structure was still required since the goal was to create a device that works most of the time, rather than in special conditions.

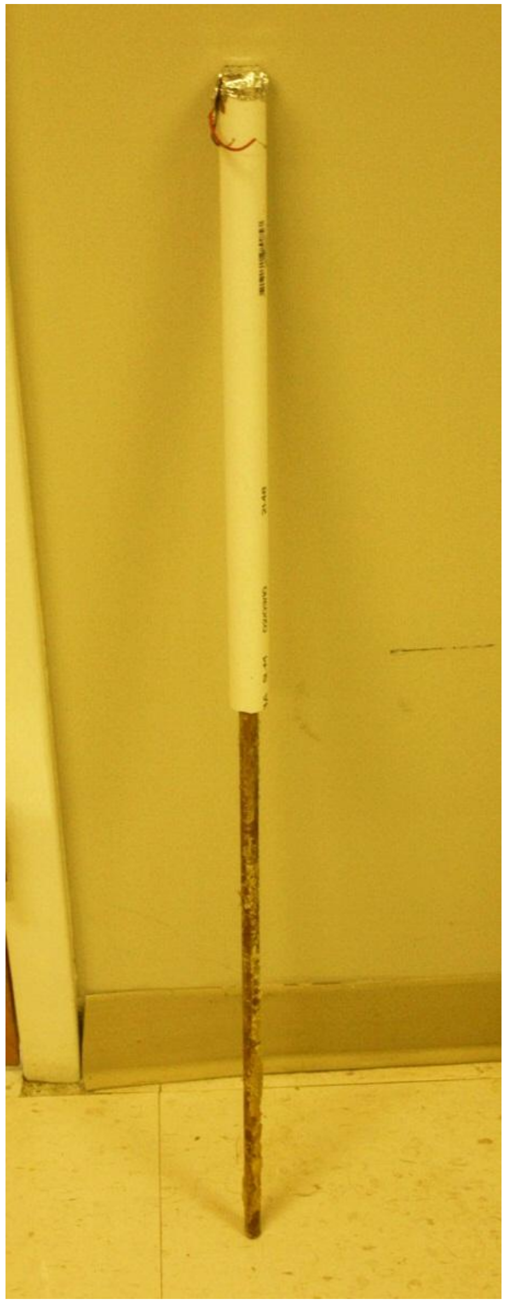


Figure 3.3: Copper rod insulated on top with PVC

3.3.3 Aluminium Plate

The third structure that was tested was an aluminium plate (18cm X 4cm) stuck to a side of the TEG. The side of the plate exposed to the atmosphere is covered with insulation tape. The output voltage obtained went above 10 mV for a few degree of temperature difference. The structure gave an output of 18 mV when the environment was 39°C and under-ground was 25°C.

The aluminium plate was used in the final design due to better performance and convenience in usage. One need not dig deep through the soil to insert a three foot Copper rod. It is enough to insert the plate a few inches into the ground. It is also more compact and easy to build. However, a custom structure made of copper can be used for best efficiency if it is permissible for the application to remain in the same place. This is described in the subsequent sections.

Figure 3.4 shows the TEG on the aluminium plate giving an output of 14.4 mV. This was not a steady output. The steady state output settled to 12.5 mV. Typically, voltage rises from 0 mV to a peak value, and then drops backs to settle at a constant value, when the heat inflow and outflow equalize. The temperature of the environment was 33.8 °C and the underground was at 25.8 °C (8 °C temperature difference).

Figure 3.4: TEG on Aluminium plate giving above 10 mV

3.4 Aluminium Plates as Heat Sources

This structure consists of the aluminium plate discussed in 3.3.3 as the source of temperature for one side of the TEG. A similar aluminium plate helps apply the ambient temperature to the other side of the TEG. The TEG is clipped to the plates. This is shown in Figure 3.5.

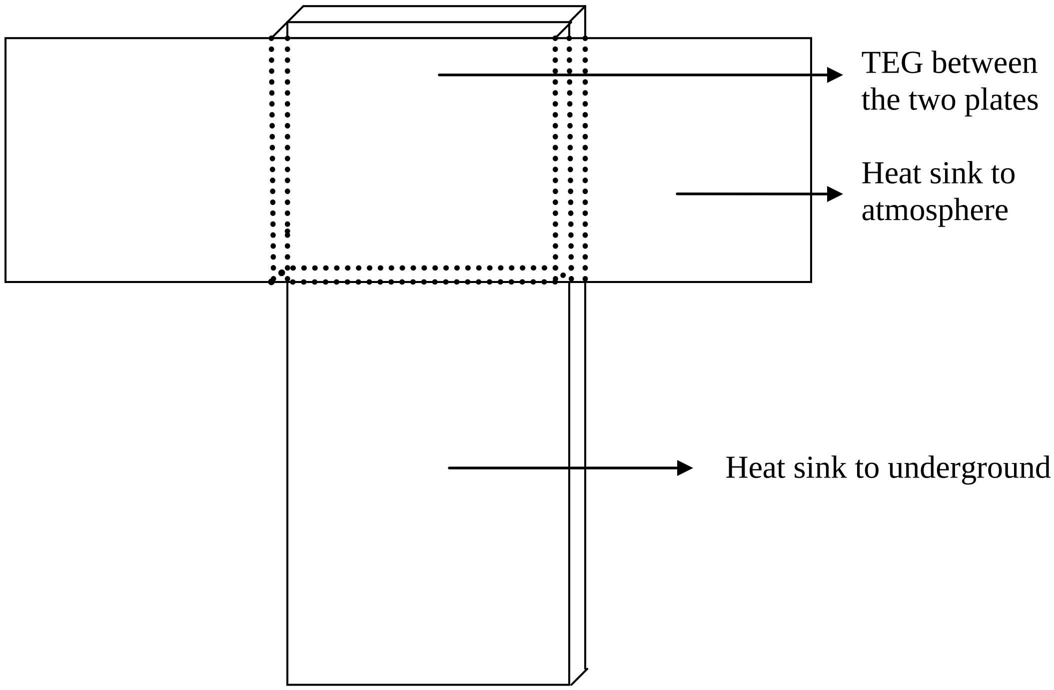


Figure 3.5: Structure with aluminium plates

The figure 3.6 shows the TEG giving 39 mV for a temperature difference of 6.2 °C. The ambient temperature was 30.8 °C, and the temperature below the top soil was 24.6 °C.

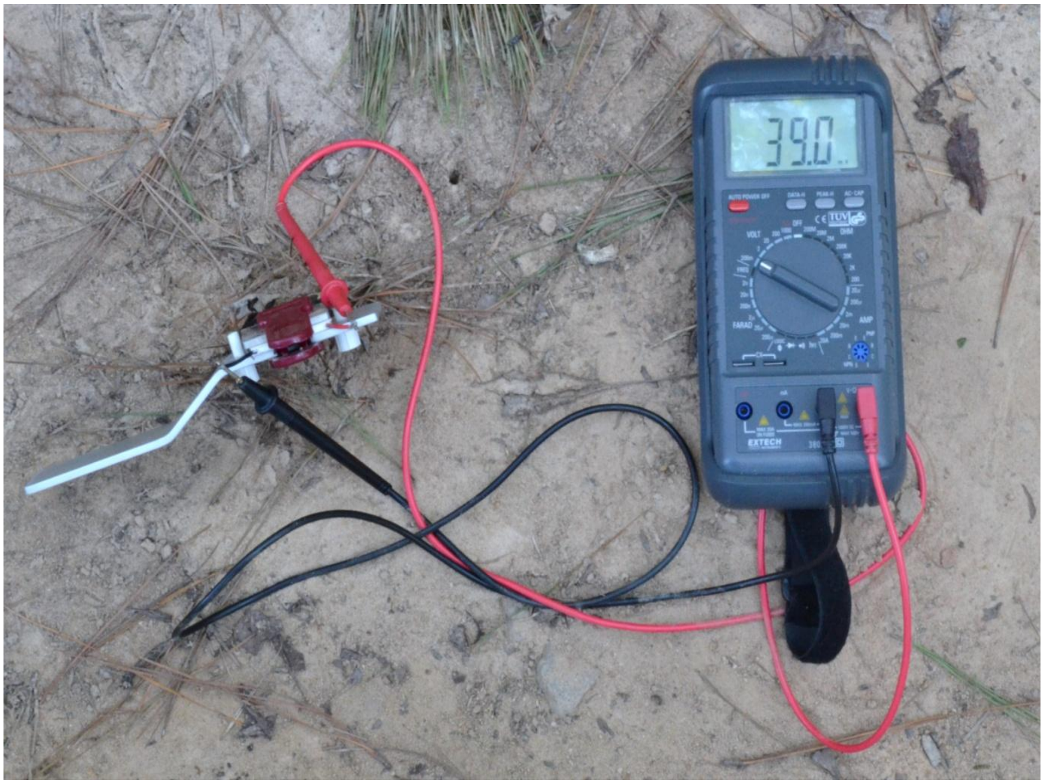


Figure 3.6: TEG with aluminium plates giving 39 mV

This output was sufficient to activate the power manager and cause the output capacitor to charge to the designed value. An important point to note is that without the heat sink attached to the plate of the TEG designed to be at the ambient temperature value, the rate of convective heat transfer from air to the TEG plate was insufficient to maintain the temperature at the desired value. This resulted in a lower voltage output from the TEG. As an example, an 8°C temperature difference between the atmosphere and the under-ground gave 12.5 mV while using the aluminium plate without heat sink (Figure 3.4). A 6.2°C temperature difference gave 39 mV with the heat sink, proving the necessity of a heat sink to maintain the ambient temperature.

3.5 Heat Transfer Factors

This section gives a brief overview of heat transfer issues and calculations, before proposing structures to maintain temperature difference between the plates of the TEG in sections 3.6 and 3.7.

Thermal conductivity, whose unit is W/m°C or W/m*K, is a factor that determines rate of heat conduction within and between solid surfaces. For solid surfaces in contact, there are deformities that reduce the contact area. For this reason, thermal contact conductance too needs to be considered for accuracy.

Heat transfer between fluids (liquids and gasses) and solids depends on convective heat transfer coefficient, whose unit is W/m^2°C or W/m^2*K. Heat transfer coefficient between aluminium and air has a value of 0.225 W/m^2*K [43].

The following text describes the formulae that need to be used with the help of an example. We consider the aluminium plate experiment conducted in section 3.3.3, with an assumption that the insulation tape is too thin to have any effect in preventing heat loss to the atmosphere. This gives us a worst case estimate of the temperature value(s) available to the plate of the TEG that is designed to be at the sub-soil temperature.

Suppose the 18 cm long aluminium plate (without insulation) is inserted into the ground such that 14 cm of it is below the ground level, and 4 cm of it is above ground level. The TEG (4 cm X 4 cm) is attached to one side of the plate that is above the ground. Let us assume that the ambient temperature is a constant T_A °C above the ground, and ground temperature right from the surface downwards is T_G °C. The arrangement with the axes is shown in Figure 3.7. Note that the TEG attached to one of the sides of the plate in the z axis is not shown in the figure for simplicity.

The temperature varies within the Aluminium plate, and so the TEG sees different temperatures at different levels (values of y) of the aluminium plate. The temperature is the same for a given value of y. For finding the temperature as a function of y at steady state, we need to form and solve differential equations. A differential equation can have multiple solutions, and as many boundary conditions as the order of the equation is needed to arrive at a solution that is specific to the problem at hand.

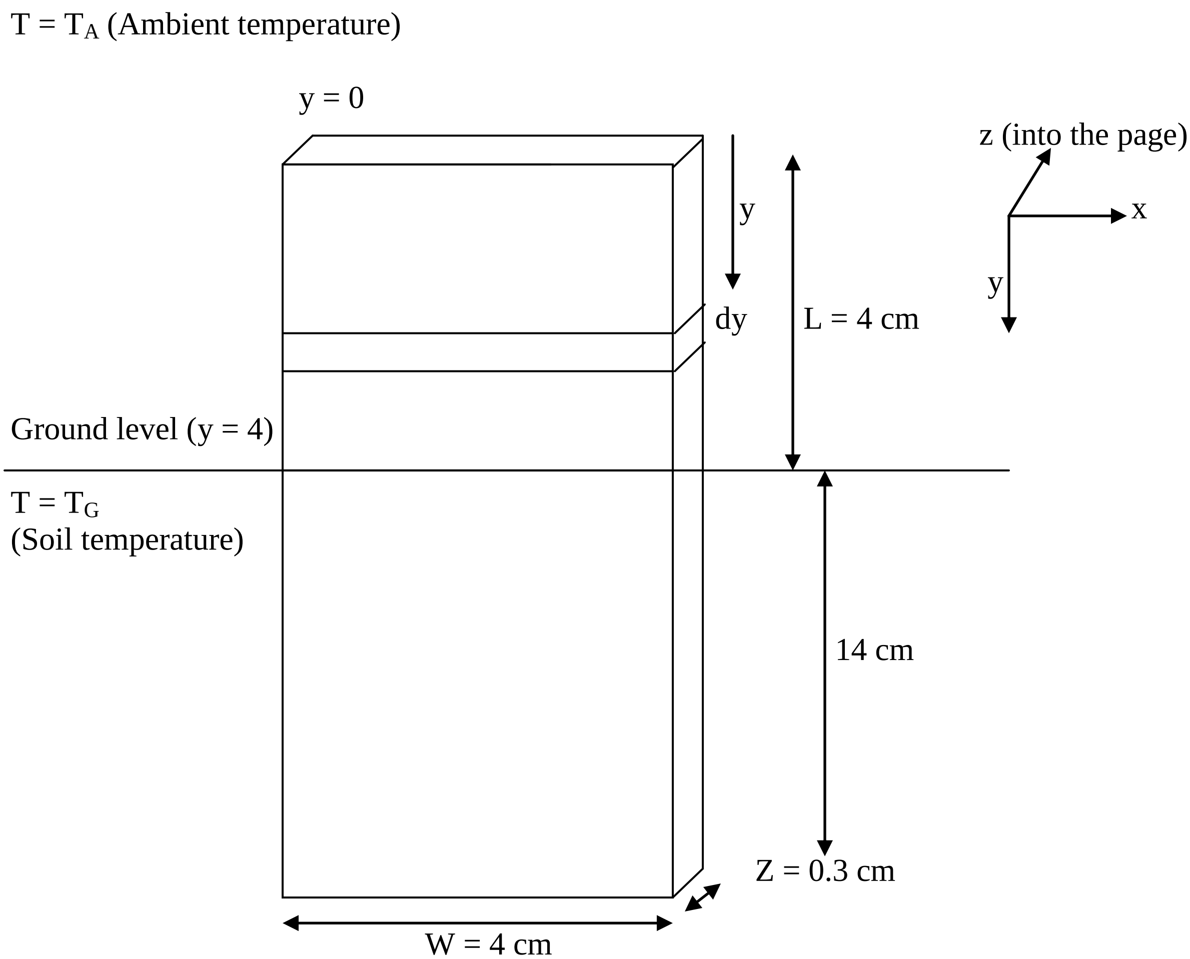


Figure 3.7 Aluminium plate with 4 cm part above ground level

At steady state, every element (or part) of the structure will settle at a constant temperature value. Before the steady state is reached, either the heat inflow, or the heat outflow is higher. If the heat inflow rate is higher, there is an increase in temperature. If the outflow of heat has a higher rate, the strip cools down. At steady state, the temperature settles to a value such that the rate of heat inflow is exactly equal to the rate of heat outflow.

Consider the section of the plate exposed to the ambient temperature. The other side of the same is attached to the TEG. At steady state, the rate of convective heat transfer to any part of this section of the plate from the air is equal to the net heat transfer by conduction to the neighboring elements in the aluminium plate.

Assume that there is no heat transfer from the environment to the top element (at y = 0) of the plate in the y direction, and the TEG does not conduct between its plates. This means that the section of the plate above the ground level has a single phase exposed to the ambient temperature. Also, assume that there is no transfer of heat in the x direction from the atmosphere. In other words, the plate's edges that go into the page for a thickness of Z do not contribute to heat transfer.

Note that heat is transferred from the atmosphere to the plate if the ambient temperature is higher than the aluminium plate's temperature, and heat is transferred from the plate to the atmosphere if the aluminium plate is at a higher temperature. The equations described below hold for both cases.

The rate of heat transfer into a strip of the plate, of thickness dy, at a distance y from the top of the TEG, due to convection from air along the z axis is given by

$H_{Al\text{-}air}$ W*dy (T_A – T),

where T is temperature of the dy strip of width W, and $H_{Al\text{-}air}$ is heat transfer coefficient between aluminium and air.

The heat flow into the strip due to conduction from the top element is:

K_{Al} WZ dT/dy $|_{y,}$

where K_{Al} is the thermal conductivity of aluminium.

The heat flow out of the strip due to conduction to the bottom element is:

K_{Al} WZ dT/dy $|_{y+\Delta y}$

At steady state net heat flow into the strip is zero. That is, the rate of heat inflow into the strip is equal to the rate of heat outflow out of the strip.

At steady state, the following equation holds true:

$$H_{Al\text{-}air} W*dy (T_A - T) + K_{Al} WZ\, dT/dy |_y = K_{Al} WZ\, dT/dy |_{y+\Delta y}$$

Rearranging,

$$H_{Al\text{-}air} W*dy (T_A - T) = K_{Al} WZ\, dT/dy |_{y+\Delta y} - K_{Al} WZ\, dT/dy |_y$$

Or, $H_{Al\text{-}air} (T_A - T) = K_{Al} Z\, d^2T/dy^2$

Or, $d^2T/dy^2 = (H_{Al\text{-}air}/ K_{Al} Z)(T_A - T)$

Using $H_{Al\text{-}air}$ = 0.225 W/m^2*K, K_{Al} = 238 W/m°C, Z = 0.3 cm = 0.003 m gives:

$d^2T/dy^2 = 0.3151 (T_A - T)$

Solving,

$T = T_A$ - ASin(y√0.3151) - B Cos(y√0.3151), where A and B are constants of integration.

For a solution, two boundary conditions are needed. One boundary condition could be that at y = 4 cm, T = T_G °C. A second equation can be formed by integrating the total heat transfer from the atmosphere into the section of the plate above the ground, and equating it to the conductive heat transfer to the element just below this part of the plate, which also happens to be just below the ground level (element dy at y = 4 cm). This condition is a result of the fact that, at steady state, heat flow into the whole section of the aluminium plate that is exposed to the ambient temperature, is equal to heat outflow to the part of the plate that is just below it. Note that the outflow and inflow are interchangeable, based on temperature values as mentioned earlier. The equation holds true for either cases.

The equation is:

$$\int_{y=0}^{y=4\ cm} H * W * \left(TA - T(y)\right)dy = (K * W * Z)\left\{\frac{dT}{dy}\right\} at\ y = 4\ cm$$

where TA = $T_{A,}$ H = $H_{Al\text{-}air}$, K = K_{Al} ,

and T(y) = T_A - ASin(y√0.3151) - B Cos(y√0.3151)

With the solution, one could find temperature at any point y cm from the top of the aluminium plate. However, the solution is approximate due to the assumptions made. Heat radiation is also neglected in the calculations. When the arrangement is such that no part of the thermal conductor is exposed to the atmosphere, such a calculation is not needed. The structures described in the next sections go completely into the ground.

When the TEG is exposed to the air, the heat transfer coefficient between ceramic material (Alumina (Al_2O_3) in this case) used and air determines the heat transfer rate, and hence the temperature of the other plate of the TEG. The area for the heat transfer is square of the side of the TEG, which is 16 cm^2. For a higher heat transfer rate a thermal conducting material with a good heat transfer coefficient and a larger surface area is needed. An example is the aluminium plate used in section 3.4, where the heat transfer occurs from air to aluminium by convection across an area of 72 cm^2, and from aluminium to ceramic (TEG plate) by conduction across an area of 16 cm^2. This would provide a temperature that is closer to the ambient temperature, onto the TEG plate. Apart from using a single plate, traditional arrangements of heat sinks can be used. For example, a fin arrangement would increase the surface area within a small space.

It was found that, by pressing the aluminium plates harder onto the TEG, more voltage difference is obtained. To increase interface conductance between the TEG and the conducting plate, ‘Thermally Conductive Adhesives’ is an option. They are available from ‘Custom Thermoelectric’, which offers other alternatives as well.

3.6 Structure for Mobile Sensors

When the sensor needs to be used at multiple locations, it is desirable to have a structure that is convenient to move around and easy to insert into the ground. The structure discussed in section 3.3.4 is designed with available structures. A structure that is more efficient in terms of maintaining temperature difference between TEG plates is described in this section.

A copper plate that is square (Vh), and has the exact dimensions as the TEG (example: 4 cm X 4 cm), is present over a vertical bar of copper (Vc) that has a large surface area, but a small thickness as shown in Figure 3.8. The whole structure goes into the ground, with the horizontal plate at the ground level, denoted by the horizontal line in the figure.

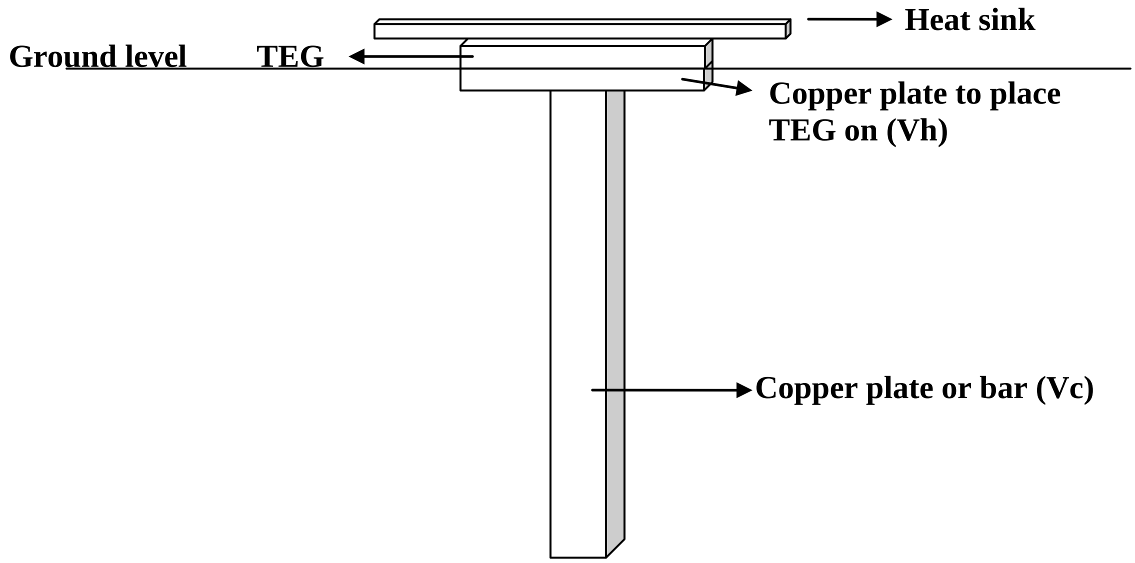


Figure 3.8: Thermal conductor to maintain temperature across a plate of TEG (for mobile sensors)

The larger area available in the vertical bar Vc will facilitate conduction of ground heat quickly to the plate of TEG on top of Vh. The plate and the bar need to be 'casted' as the contact between the two is a bottleneck as far as temperature transfer is concerned. Gluing them together, or placing cut plate and bar are not desirable as we are dealing with transfer of small amounts of temperature difference. Gluing might cause slower heat transfer, while placing cut surfaces with non-uniformities will decrease the area of contact between the two. Welding too would cause reduced contact area.

On top of the TEG on the horizontal plate Vh, a rectangular or circular plate made of copper must be placed in order to facilitate transfer of ambient temperature to a larger area as described in section 3.5. This is the heat sink shown in the figure that acts as a source of ambient temperature to the top plate of the TEG.

The vertical copper plate or bar (Vc) must be long enough to make sure that the ground temperature is applied to the bottom plate of the TEG. This length depends on two factors: (a) soil density which determines the surface contact conductance between soil and Vc, and (b) the depth required to obtain sufficient temperature gradient.

From Figure 3.1 we see that in June to August period, the average temperature difference between the surface and two feet below the ground is close to 3 °C. This could create 1-2 °C temperature difference between the TEG plates after losses. Vc should be more than two feet long based on this data. However, it is the instantaneous temperature difference that determines the ability to harvest power, and not the average temperature difference. In Raleigh, NC, it was observed that it was easy to obtain a temperature difference of 2-3 °C for most parts of the year, between the environment and a depth of 10 cm. By keeping Vc as 10 cm, one could harvest the energy.

The heat transfer rate into the heat sink from the environment and the heat transfer from it to the TEG, or vice versa, determines the steady state temperature applied to the top part of the TEG. It is a challenge to arrive at a model for thermal conduction between the plates of the TEG as the thermocouples will form paths of thermal conduction with air gaps between them. This air exhibits convective heat transfer, and there is heat loss through the sides of the TEG. One could neglect the effect of air gaps when the conduction through thermo-couples dominates the heat transfer rate, or one could over-design the heat sink area by assuming a higher conduction rate between the TEG plates.

Though the surfaces appear smooth to the naked eye, there are irregularities on the TEG plates and copper or aluminium plates. This reduces the effective area that can be used for conduction between solid surface contacts. Using thermally conducting glues will fill up the gaps and apply the temperature difference to the TEG plates more effectively.

Due to lesser density (mass per unit volume) of aluminium compared to copper, an aluminium structure would be lighter in weight and easier to carry around. When desiring for such a quality, the structure described above can be made from aluminium instead of copper. Such a structure would also be cheaper. The trade-off is the requirement of a larger area for Aluminium due to its lower thermal conductivity compared to that of copper's.

3.7 Structure for Fixed Sensors

A more efficient structure in terms of felicitating an even higher duty cycle of operation of the sensor would require adding additional insulation, and a longer structure into the ground. This structure would not be mobile, and needs to be placed at a single location. This could be used for monitoring-sensors such as water-flow indicators.

The structure that goes into the ground is shown in Figure 3.9. The horizontal plate on which the TEG is placed has the dimensions of the TEG. Below this plate, a rod of copper goes into the ground. A part at the top of this rod is covered with a thick insulator, which prevents it from coming into contact with the temperature at the top part of the soil that is closer to the ambient temperature. The rod is circular so that the area available for leakage is low. The downside is the reduced rate of heat transfer from the ground to the horizontal plate in contact with the TEG. An optimal structure could be arrived at by mathematical calculations or simulations. A mechanism like the one used in vacuum flaks will offer a convenient solution. Vacuum prevents heat transfer by conduction or convection.

As used in Figure 3.8, it is necessary to effectively apply the ambient temperature onto the TEG plate using a heat sink. The top plate of the TEG is connected to a circular or square plate of copper for faster transfer of heat from the environment, and is not shown in Figure 3.9. Conducting glue on both plates of the TEG ensures that the non-uniformities in the solid surfaces do not slow down the heat transfer rates.

The length of the structure into the ground, and the amount of insulation at the top part of the rod is based on the temperature gradient available as well as the density of the soil as explained in the previous section. Based on experiments at that particular location where the sensor is designed to be used, values must be chosen.

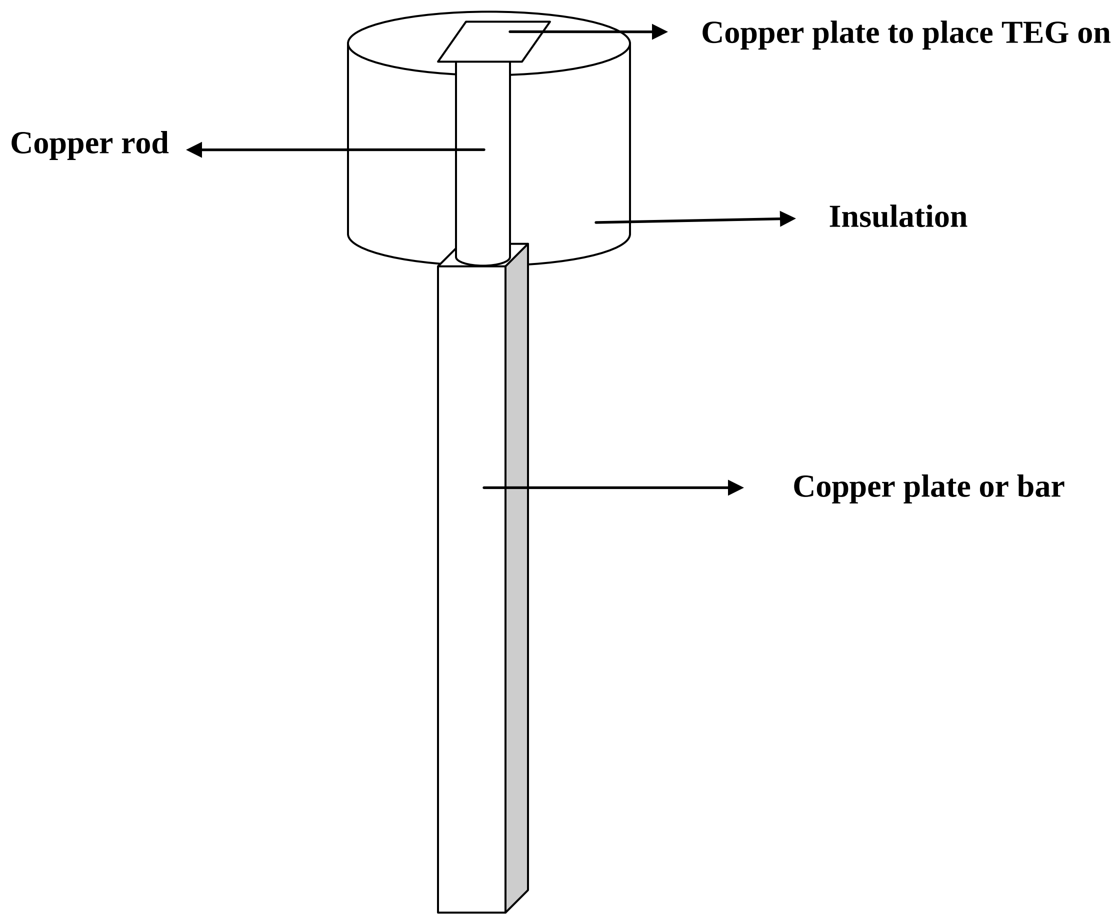


Figure 3.9: Thermal conductor to maintain temperature across a plate of TEG (for fixed sensors)

From Figure 3.1 we see that in June to August period, the average temperature difference between the surface and five feet below the ground is close to 5.6 °C. An insulation of two feet will ensure that we apply this 5.6 °C temperature difference compared to 3 °C in section 3.6. This model charges the output capacitor more quickly due to a higher voltage output from the TEG. This in turn would result in a higher duty cycle of operation of the sensor. The thickness of the insulation can be selected based on the material used and the duty cycle requirements. A thicker insulation or a material with lower thermal conductivity will result in a higher duty cycle. Either a material can be chosen and its thickness determined, or an appropriate material can be chosen for a given thickness. As an example, a pipe with vacuum would ensure very little heat transfer (only mode is through radiation).

As mentioned in the previous section, instantaneous temperature matters, and not the average temperature. It was observed that temperature remained pretty constant below an inch at Raleigh, NC. A rod of a length of one foot with an inch of insulation at the top would suffice to harvest energy and have a higher duty cycle of operation for the sensor compared to the structure in section 3.6.

CHAPTER 4

Power Manager

4.1 Function of Power Manager

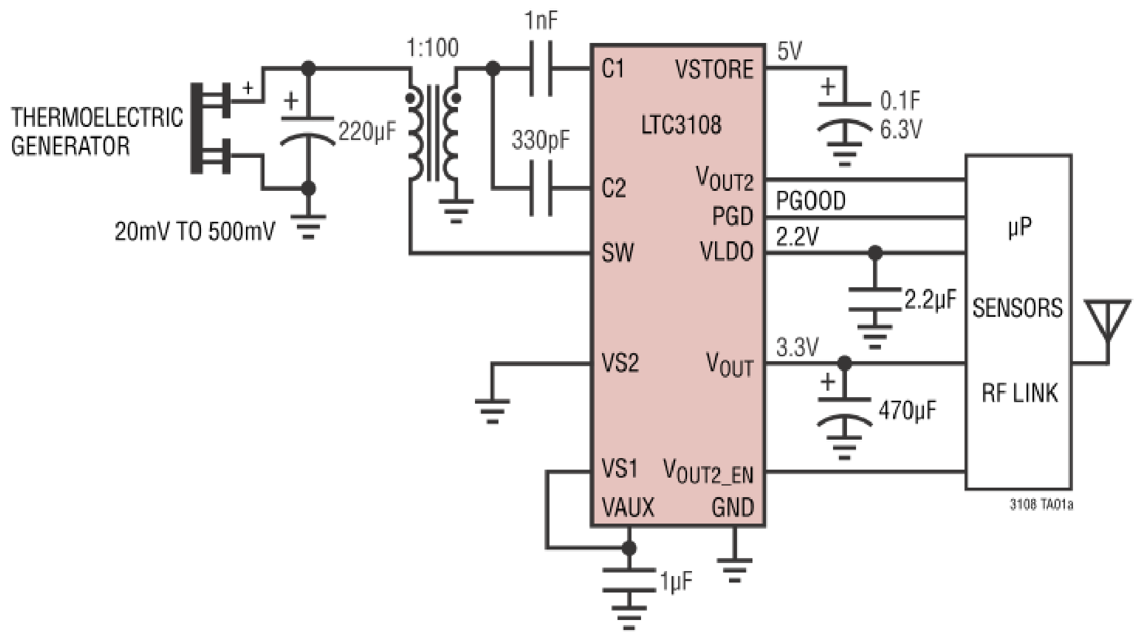
The electrical circuit required for the energy harvester is a power manager, which makes sure that the power is supplied to the sensor when required. It performs two main functions. The small input voltage from the transducer is stepped-up using a DC-DC converter. Next, it charges up a capacitor or super capacitor to deliver current to the sensor when requested. Other energy-harvesting devices propose to trickle charge a rechargeable battery. This will ensure that the sensor functions all the time, and the harvested energy helps prolong the use of battery before the next phase of recharging or battery replacement. In other words, the operational life of the sensor is prolonged.

The choice of energy storage is between a capacitor or a super-capacitor, and a battery. A capacitor is cheaper, lighter in weight, and lower in area, than a rechargeable battery, but the leakage is higher. Rechargeable battery, on the other hand requires a higher upfront cost, but has the advantage of lower leakage. A battery can deliver a steady voltage, while a capacitor's voltage decreases as it discharges. A capacitor or super-capacitor can be charged and discharged innumerable times, while the number of such cycles is limited for batteries.

4.2 LTC3108

The power-manager used for this project is LTC3108 from Linear Technologies. Simulation of the chip can be done using 'LTSpice IV'. The tool is free and can be found in at http://www.linear.com/product/LTC3108. Both the tool and a demo circuit for LTC3018 are given in the link. The chip is designed especially for energy harvesting.

Figure 4.1 shows the circuit that was built in this project, with the exception of the microprocessor sensor. A soil NPK analyzer was used instead.

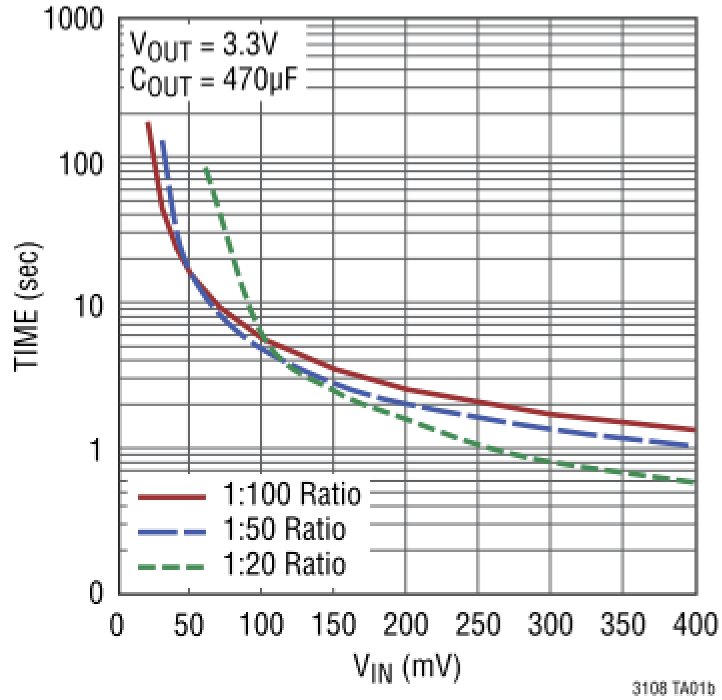


Source: [44]

Figure 4.1: System level view of the energy harvesting device

The input to the DC-DC converter comes from the TEG, and needs to be at least 20 mV for charging the output capacitor. The PGD signal indicates to the sensor that the capacitor is ready to power the sensor. It is not used for this project. In a commercial application it must be made use of in order to ensure that the reading that is shown is accurate. For example, in analog sensors where current flow determines the swing of a needle, a higher voltage will pass more current, which would cause a higher deflection. This circuitry needs to be integrated into the sensor circuitry or a new power manager.

The minimum input voltage that charged the output capacitor was 25 mV. Figure 4.2 shows the time taken to charge the output capacitor to 3.3 V while using a 470 µF output capacitor.

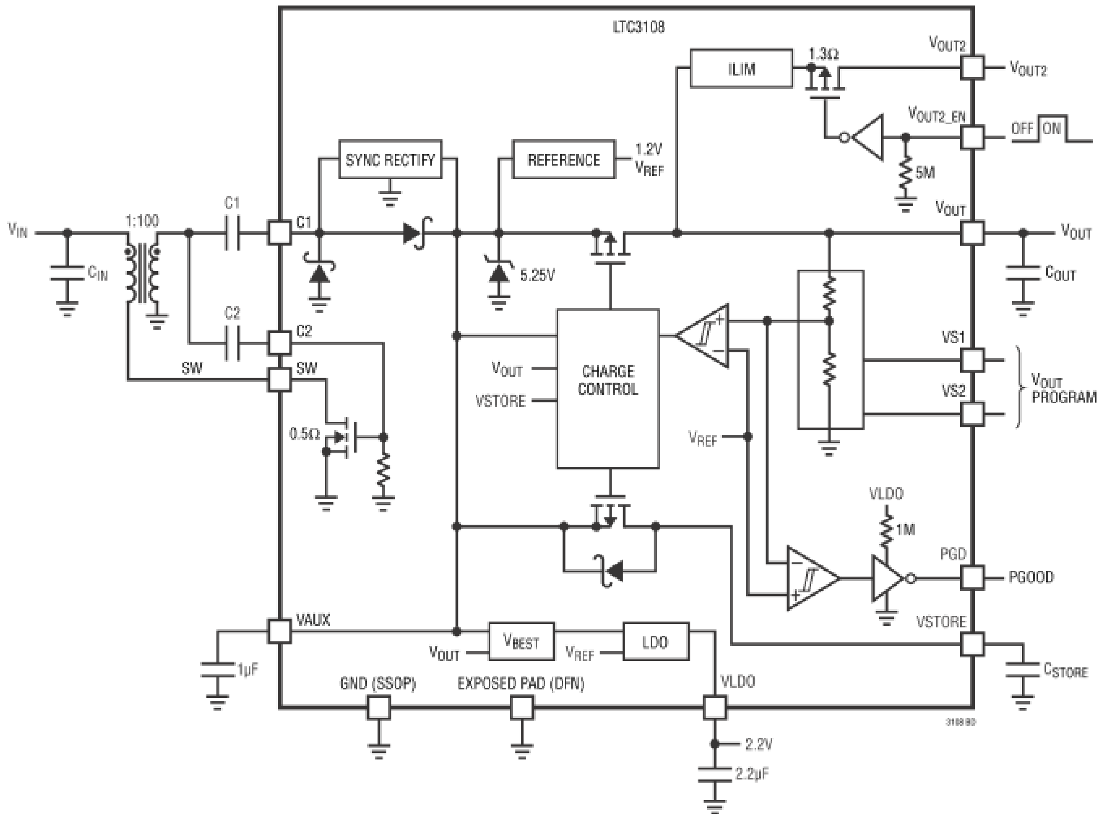


Source: [44]

Figure 4.2: Vout charge time vs Vin

A 1:100 transformer was used for this project. From the graph we see that the output capacitor takes more than two minutes to get charged to 3.3 V. This defines the time the sensor cannot be used, once a value is read.

The internal block diagram of the LTC3108 is shown below:



Source: [44]

Figure 4.3: Inside LTC3108

LTC3108 is available in DE package with 12-lead plastic DFN, and a GN package with 16-lead plastic SSOP narrow. The 12-lead DE package surface mount chip was selected to be used in this project. It offers the advantage of being smaller. 1:100 step-up transformer was used for stepping up a 25 mV input. Transformer samples from Coilcraft were obtained, and part number 'LPR6235-752SML' was used. Seven capacitors were required to be used for the power manager.

4.3 PCB Design

The PCB was designed to have the capacitors, LTC3108 and the transformer, using EagleCAD, which is from CadSoft (http://www.cadsoftusa.com/), and is free to download and use. Custom components were created for the transformer and the LTC3108 chip.

The following are the components put on the board:

1. LTC3108
2. LPR6235-752SML (1:100 step-up transformer)
3. 0.1 F
4. 2.2 µF
5. 470 µF
6. 1 µF
7. 330 pF
8. 1 nF
9. 220 µF

Here are the schematic and board layout as appearing in EagleCAD:

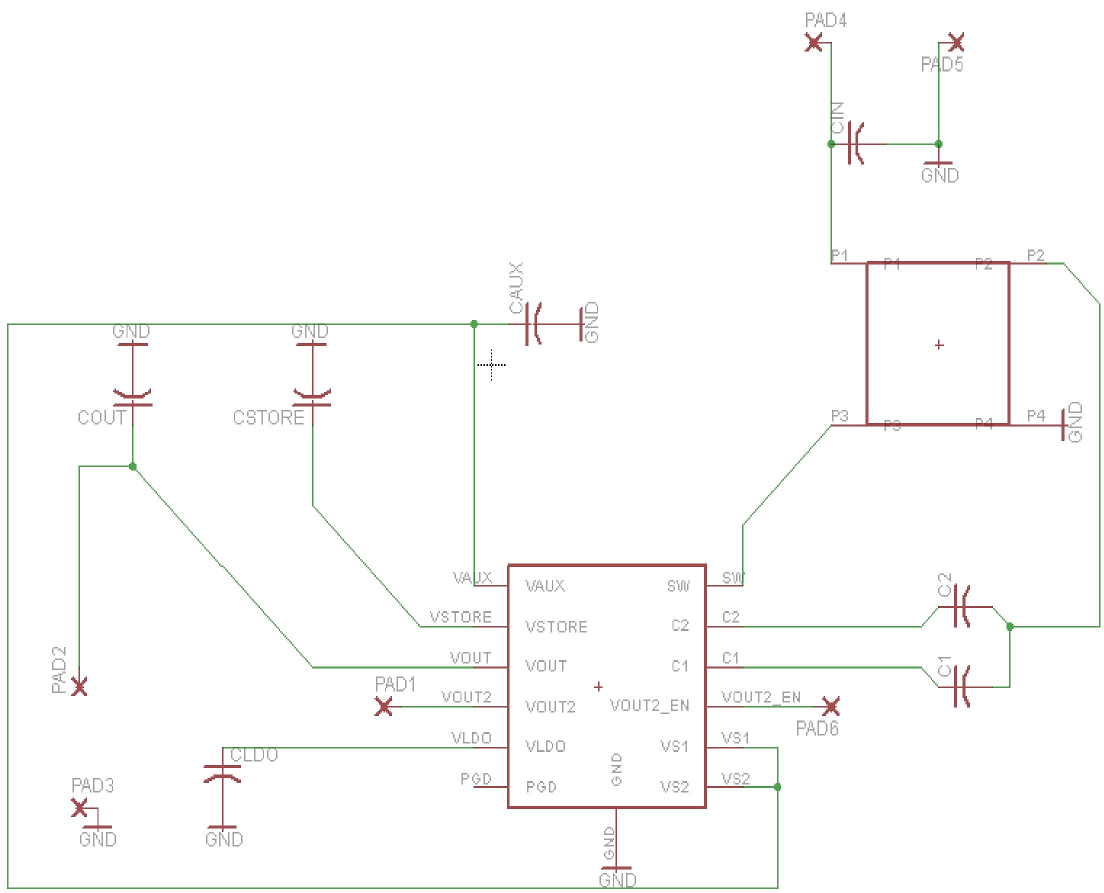


Figure 4.4: Schematic of power manager

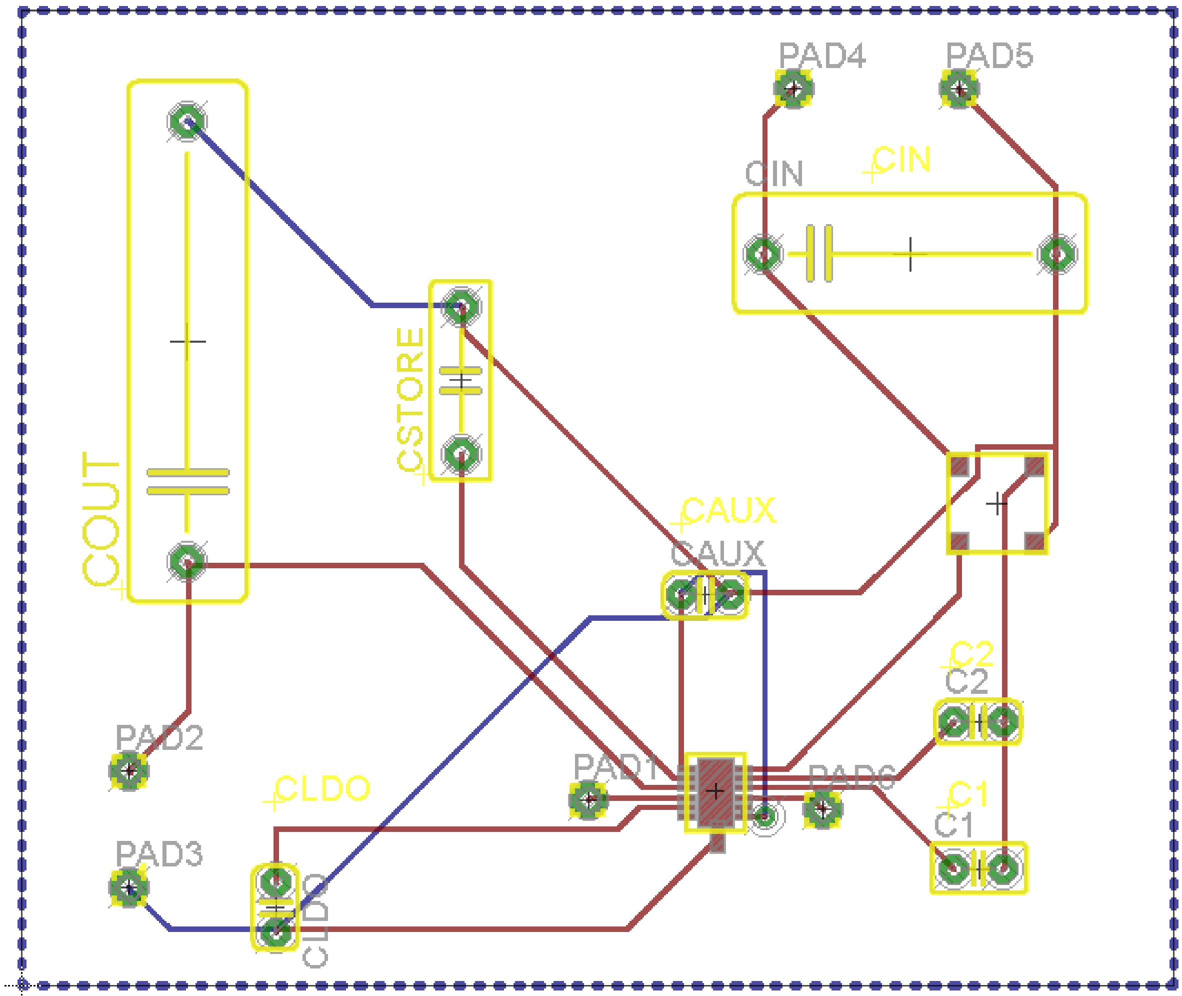


Figure 4.5: PCB layout of power manager

The pins were connected as per the datasheet of LTC3108. The following cases had different options available, and the connections that were made are indicated as follows:

1. Vout2 was not used, and was left open
2. Vout2_en was not used, and left open
3. Vs1 and Vs2 were both connected to Vaux in order to get the maximum output of 5 V

The options for Vs1 and Vs2 are either GND or VAX. The values of Vout for all combinations are shown in the table below.

Table 4.1: Vout for VS1 and VS2 combinations

VS2	**VS1**	**Vout**
GND	**GND**	**2.35 V**
GND	**VAUX**	**3.3 V**
VAUX	**GND**	**4.1 V**
VAUX	**VAUX**	**5 V**

Source: [44]

The PCB was a two-layer board ordered from Advanced Circuits (http://www.4pcb.com/). The PCB with all the components soldered, is shown in Figure 4.6.

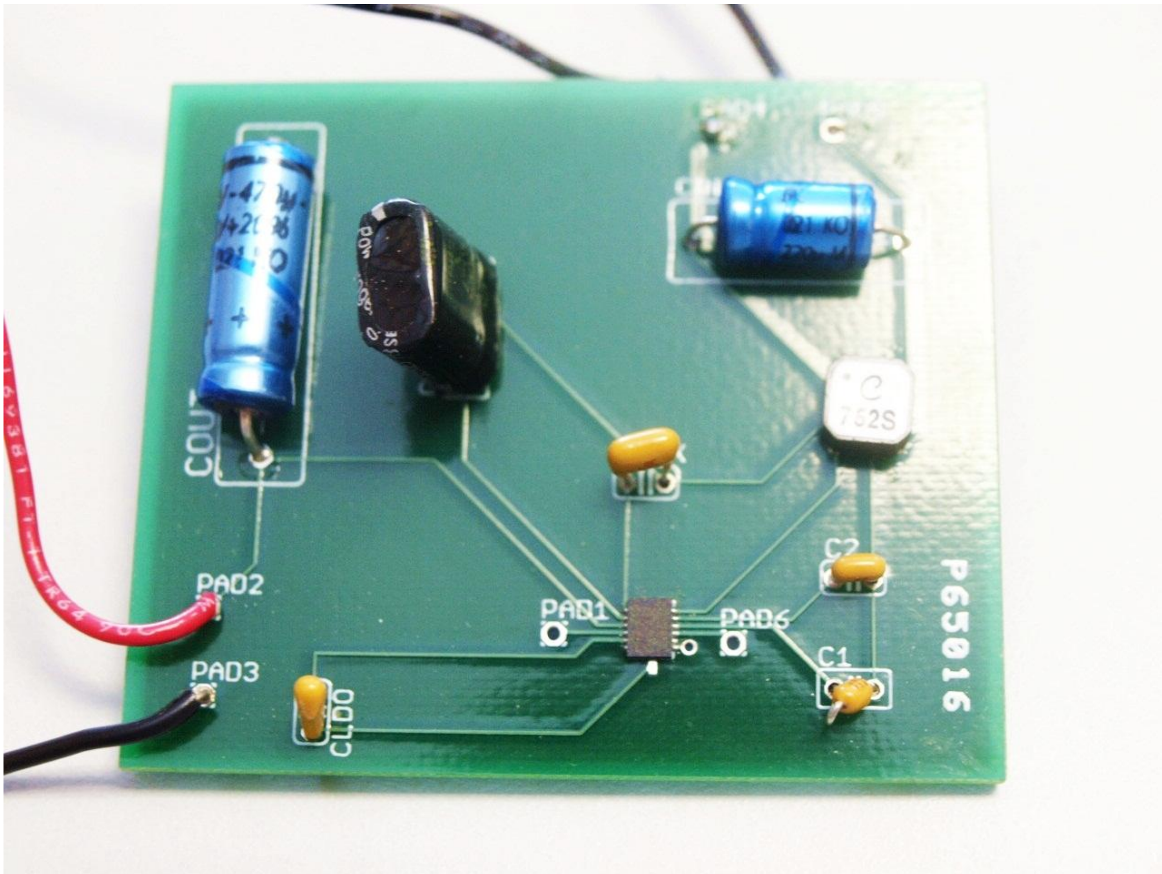


Figure 4.6: PCB of power manager circuit

4.4 PCB Testing

A PCB was made by connecting VS1 and VS2 to GND and VAUX respectively to give an output of 3.3 V, while in another both VS1 and VS2 were connected to VAUX to give an output of 5 V. Let the PCBs be called PCB1 and PCB2 respectively.

The Power manager circuits were tested by giving a constant input voltage using a power supply. The performance of PCB1 is shown in table 4.2, and the performance of PCB2 is shown in table 4.3.

Table 4.2: Vout vs Vin for power manager designed for 3.3 V output

Input Voltage	**Output Voltage**
15 Mv	**Fails to charge up**
25 mV	**2.99 V**
35 mV	**2.99 V**

Table 4.3: Vout vs Vin for power manager designed for 5 V output

Input Voltage	**Output Voltage**
15 mV	**Fails to charge up**
25 mV	**4.70 V**
35 mV	**5 V**

35 mV input to PCB2 gave an output of 5 V. Figure 4.7 shows an input of 0.03 V (30 mV) charging the output capacitor to 5 V. The voltage at the terminals of the input capacitor showed 35 mV using the higher resolution Multimeter.

The PCB does not charge the output capacitor to the full capacity for a 25 mV input, but to an intermediate voltage close to the expected value. The PCB designed for giving 5 V, produced a 5 V output when the input (after drop in thermocouple) was 35 mV

Table 4.4 shows that between 25 mV and 30 mV, the output capacitors charge up from 4.6 V to 5 V. Until one is sure that the output capacitor is charged to 5 V, the sensor must not be powered. In cases where current in a circuit is shown to indicate a value, lower voltage results in a lower current. In order to overcome this potential error, PGD signal from the LTC3018 must be used. The PGD signal helps in making sure that the output voltage is under regulation before being used to power the sensor.

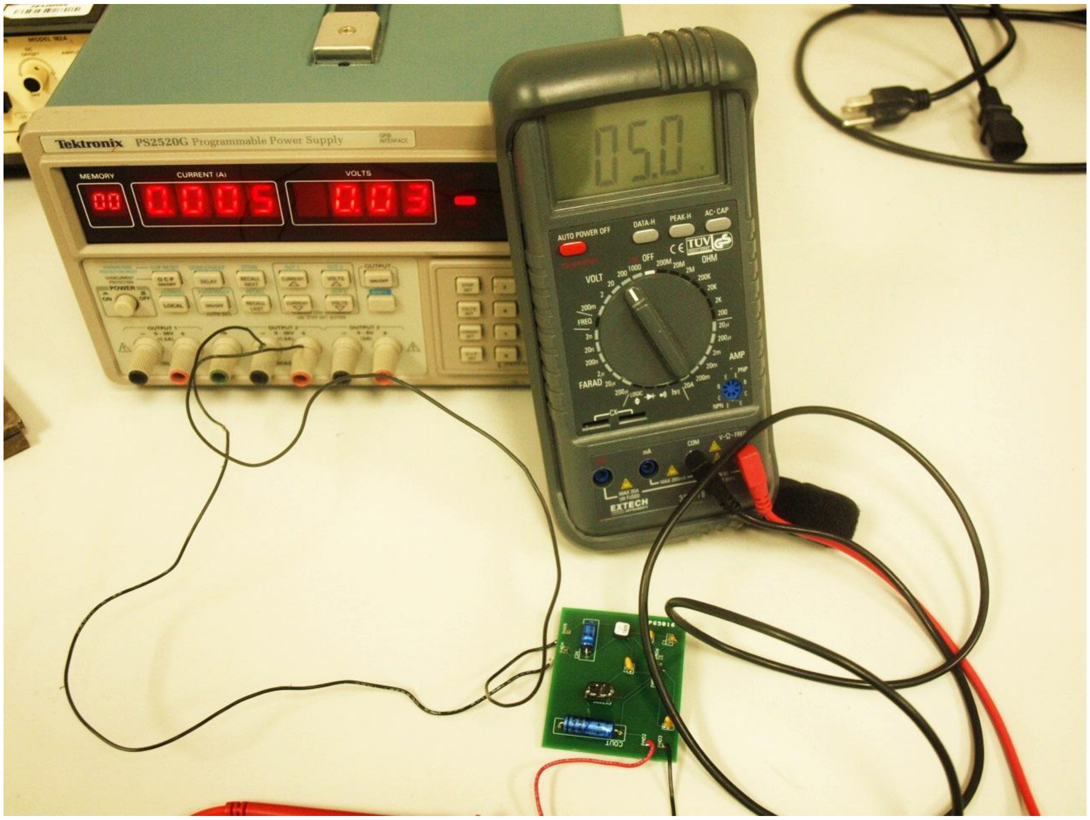


Figure 4.7: Output capacitor charging to 5 V for 30 mV input

CHAPTER 5

Agricultural Sensors and Batteries

5.1 Sensors for Agriculture

The sensors that needed to be used in this thesis were selected based on the criteria of low power consumption. They require an input voltage that is below 5 Volts, which is the maximum that the LTC3108 can supply.

Soil moisture and NPK content sensors were analyzed for being used. Moisture sensors are available from NRG-meter and Rapitest which run without battery. They have an insulator separating two conductors to form a battery along with the moist soil. The readings on the meter were proportional to the current that flowed through the conductors. They indicate the level of moisture as dry, moderate and high, and do not indicate the quantitative values.

More accurate moisture-meters are based on conduction of current in the soil. Gypsum is a common substance that absorbs moisture, and is used in chip-integrable sensors from “Irrometer”. More the moisture content, lesser is the electrical resistance. These meters also require data loggers which consume more power, apart from being expensive. Accurate sensors also tend to consume more current (8 mA), which makes them disadvantageous for use in energy-harvesting applications. Other types of moisture sensors use varying dielectric constant based on moisture content. This can be done in terms of capacitance measurement or using a Time-domain reflectometer (TDR).

Two soil NPK/pH indicators that are battery powered, one called “Soil Analyzer” and one from “Ferry Morse”, were used in this project. They both were similar, and indicated either pH or NPK content. They needed an AA battery that produced 1.5 V. Due to this reason it was expected that they could easily be powered from the LTC3180.

In the sensors used, a higher input voltage would produce a higher deviation, which would not be the correct value. The values are calibrated with respect to a constant voltage source, and a lower or higher voltage would require recalibration. When the output capacitor of the power manager is charged to the full potential of 5 volts, a resistor in series would provide the correct voltage to the meter. This resistor needs to be selected based on the current drawn by the meter. The meters used here take an input of 0.3 mA, and hence the resistance value needs to be about 12 Kilo-Ohms.

The output capacitor charged up to a value below the maximum value of 5V when the input was between 25 mV to 30 mV. A value higher than 30 mV is necessary for charging the output capacitor to 5V. This creates additional problem because one would not know what resistor to put in series with the output capacitor. If the correct value is not used, the indication in the meter would be wrong. For this purpose, it is imperative that the PGD signal from LTC3108 is used, and a sensor must be designed to make use of it. In other words, meters need to be designed to suit the purpose of energy harvesting using a chip like LTC3108. Sensors can also be optimized for low-power. Lesser the power requirements, more convenient it is for the energy-harvesting device to power it.

Sensors are either destructive or non-destructive. The former type, destroy the matter that they measure. For this reason, non-destructive sensors are preferred. In case of Nitrogen content measurement, both Nitrate (NO_3^-) and Ammonium (NH_4^+) need to be measured. ISFET (Ion-selective FET) can be used to measure the content of a particular ion. This will have good accuracy than a one that just claims to measure the overall Nitrogen content. ISFETs in general, can be used for quantitative analyses of chemical salts.

A few of the non-destructive methods are described here. In XRF Spectrometry, high energy X-rays or gamma-rays are bombarded onto the sample and the emission of radiation will indicate the kind of elements present. This however will not indicate the quantity of the element. In another approach, a strip of material is dipped in the soil solution, and the color change is compared with a look-up table to determine the Nitrogen content. Sometimes indicator plants are grown, and Nitrogen or protein content in them gives an indication of the Nitrogen content in the soil. In another mechanism, the amount of green color in the leaves is used to get an indication of the amount of Nitrogen content.

There is lot of potential for use of low power electronics in an agricultural field [34]. Sensors for Nitrogen salt content in the soil are under research. It is claimed that the sensors that come up give varied results for the same soil-matter. The project focused on integration of devices, and not much on accuracy, and so more accurate and expensive sensors were not used. The meters used here produce a deviation of a needle that is proportional to the current flow, and do not have a separate data logger to power.

5.2 Rechargeable Batteries

Batteries are of two kinds: Primary and Secondary. The primary batteries can be used only once as the chemical reaction that occurs on drawing current is irreversible. In the case of secondary batteries, the reactions are reversible on application of current in a direction opposite to the direction drawn from. They can only be recharged for a certain number of cycles, after which they need to be disposed off. Rechargeable batteries have a higher upfront cost, but lower average cost over time.

The mAh rating indicates the hours of operation at a given current. This indicates the life of a charged battery. Silicon Labs has ‘Battery Life Estimator’ software tool, and an Excel sheet with a number of parameters available for estimating the battery life called ‘Battery Life Calculator’. These give estimates of battery life while use in microcontroller applications.

The life of a rechargeable battery is given by the total number of times the battery can be recharged. The normal usage of rechargeable battery is to start using a fully-charged battery until charge drains out completely or almost completely, recharged to full capacity, again discharged fully, and so on. The number of times this charging and discharging cycles happen is limited, and life of each type of rechargeable battery is characterized by the number of these cycles. It is not recommended to recharge the battery when it is partially discharged (or used) as this would bring down the life.

Table 5.1 shows a few characteristics of some commonly used battery types.

Table 5.1: Characteristics of common rechargeable batteries

	NiCd	Lead Acid	NiMH	Li-ion	Reusable Alkaline	Li-ion polymer
Commercial use since	1950	1970	1990	1991	1992	1999
Gravimetric Energy Density (Wh/kg)	45-80	30-50	60-120	110-160	80 (initial)	100-130
Cycle life (to 80% of initial capacity)	1500	200 to 300	300 to 500	500 to 1000	50 (to 50%)	300 to 500
Typical fast charge time	1h	8-16h	2-4h	2-4h	2-3h	2-4h
Overcharge tolerance	moderate	high	Low	very low	moderate	low
Nominal cell Voltage	1.25V	2V	1.25V	3.6V	1.5V	3.6V

Source: [1]

For energy harvesting devices, trickle charging of rechargeable batteries are suggested as a possible application. Trickle charging is normally used for two cases. It is used as the final stage of charging a battery, or used to compensate for the self-discharge or leakage of a battery.

In the case of solar energy harvesting, batteries are charged up when not in use. The sun light can be used only during sunshine hours, and not in the night. When energy is available and not requested, it is stored for later use. Trickle-charging batteries are economical in this case, since the availability of a huge quantity of harvested energy outweighs the reduction of battery life brought about by not following the rule of fully discharging and charging. A person considering use of an energy harvesting device for trickle charging must address the problem of reduction of battery life brought about by trickle charging partially discharged batteries.

When an energy harvesting device is used for the purposes of charging a battery, we must take three factors into consideration. Just like a normal battery charger, it must provide the availability of charge, an optimized rate of supply of this charge to the battery, and a stoppage of charge supply so as not to overcharge the battery. The rate of charge supply or the current into the battery must make sure that the rate of chemical reactions occurring inside the battery is under control. If the rate of charge supply is more, then excessive chemical reactions will cause heat and gas production that will destroy the battery. The energy harvesting device supplies a small amount of charge in pulses. Both of these are good qualities, and satisfy the first two factors mentioned. The last part for a charger is to stop supplying charge when all the reactions are over. If not stopped, there will be heat and gas production that will destroy the battery. The method of stoppage used depends on the type of battery, and normally a small change in either voltage or temperature is used to cut-off the supply of current into the battery. It can also be done using timers [38]. This is another challenge an energy harvesting device needs to address when used for trickle charging a battery.

SLA batteries and NiCd batteries are relatively more tolerant to trickle charging after the battery is fully charged, compared to NiMH and Li-ion. Never the less, NiCd cells too produce gases which damage the batteries on over-charging [38]. Charge termination methods used for common rechargeable batteries are shown in table 5.2.

Table 5.2: Charge termination methods for common rechargeable battery types

	Charge Termination Methods			
	SLA	Nicad	NiMH	Li-Ion
Slow Charge	Trickle OK	Tolerates Trickle	Timer	Voltage Limit
Fast Charge 1	Imin	NDV	dT/dt	Imin at Voltage Limit
Fast Charge 2	Delta TCO	dT/dt	dV/dt=0	
Back up Termination 1	Timer	TCO	TCO	TCO
Back up Termination 2	DeltaTCO	Timer	Timer	Timer

TCO = Temperature Cut Off

Delta TCO = Temperature rise above ambient

I min = Minimum current

Source: [38]

NiMH and Li-ion cells have higher energy density than NiCd. That is, for the same weight, the former two offer more energy. NiCd gives a steady charge of 1.2 V for a larger part of the discharge cycle. NiCd has memory effect and lazy effect. When the battery is charged to a certain voltage a multiple number of times, the battery does not charge to the full charge in the subsequent recharging phases. The battery charges to the lower voltage that it was charged to in the previous charging cycles. This is known as memory effect, as it ‘remembers’ the voltage from previous charging cycles. To prevent this, we must ensure that we trickle charge to the full potential before using the battery. Trickle charging up to a random level, and then using the battery might cause this problem in an energy-harvesting device. The lazy effect happens when the battery is repeatedly overcharged. Here, the battery appears to be fully charged, but discharges quickly. This can be recovered by a few full charge-discharge cycles, but at the expense of reduction in the battery life.

When temperature change is being used to cut-off the battery charging to prevent over-charging, one must ensure that the battery is not hot before commencing to recharge. A battery could get hot on usage, and due to this charging could get cut-off. For manual recharging, this can be taken care off, but in an autonomous sensor with no human intervention this becomes an additional challenge. [35] gives a brief description about battery charging.

In case of chip compatible solutions, thin-film lithium-ion batteries can be used. They are thin (few millimeters), and can be stacked to give a higher voltage. Research is still on, in the making of these batteries. These will be good alternatives to the bulky batteries used at present.

5.2.1 Trickle Charging With Energy Harvesting Devices

The output of the energy harvesting device needs to go through a control circuit to make sure that the output capacitor is connected to the ends of the battery terminals only when its voltage is above the voltage rating of the battery. Suppose the rechargeable battery has a rating of 1.5 V. The output capacitor needs to be connected when its voltage reaches 5 V, and then cut-off from the battery after its voltage drops down to 1.5 V. If this is not ensured, the battery will charge up the capacitor, that too in the reverse direction. This is also a problem while using electrolytic capacitors. An easy way is to use a diode that allows current in only one direction. The p-side of the diode must be connected to the positive of the output capacitor, and the n-side to the battery. PGD signal from LTC3108 could be used to make pulsed discharges of the output capacitor once it reaches its full designed voltage.

The energy harvesting device has an output capacitance of 470 μF, which is charged up to 5 V. The amount of charge stored in the output capacitor is equal to the product of capacitance and voltage, which is 2.35 mC. The capacitor does not discharge all of its charge. For charging a AA battery to maintain full charge, which is typically 1.5 V, the capacitor can at the most discharge from 5 V to 1.5 V. Multiplying the voltage difference which is 3.5 V, with the capacitance, gives 1.645 mC.

The sensor that was used in this project took in 0.3 mA. Suppose two seconds are necessary to take a reading from the meter. This would cause a discharge of 0.6 mC. Since the energy harvesting device is able to supply 1.645 mC in a single cycle of operation, the charge given to the sensor can be got back by the battery. The cycle of operation here means the process of charging the capacitor by harvesting the energy, and then using this to charge the battery.

Trickle charging can be done to charge up the battery to full potential. The trickle charge rate of a battery of capacity C is normally C/10. For a 600 mAh NiCd battery, this will come to 60 mA. Lower charge rates will take a longer time, and a rate of C/50 will never be able to fully charge a battery. A C/50 rate is 12mA. It is claimed that 14 to 16 hours of charging at C/10 rate, charges the battery to full potential. Any further charging would accelerate the deterioration of battery [39].

Batteries have a self-discharge rate due to leakage. Trickle charging is done in this case to make sure that a fully charged battery remains full. The leakage or self-discharge rate of NiCd and NiMH is about 1 % per day at room temperature. This means that a 600 mAh battery loses 6 mAh each day. Unlike in the previous case where trickle charging is used for charging a discharged battery, a smaller rate of charging will do. The rate is anywhere from C/50 to C/20. For a 600 mAh battery, this would be 12 to 30 mA [39].

All the above rates are for continuous trickle charging. For a pulsed charger, which is the case for energy harvesting devices, the rate needs to be even higher. At least a C/10 charge rate would be desirable [39].

Once the output capacitor of the energy harvesting device is discharged, an interval of time is needed to restore the charge. The data sheet of LTC3108 shows that the output capacitor stores 3.3 V in about two minutes. In a 120 second interval, 1.645mC are supplied to the battery. This would give a rate of 13.7 µA. This is too low compared to even C/50 rate to have any practical significance when used for maintaining full charge in a battery.

In summary, the charge consumed by the sensor can be put back into the battery, and the rate of charge supply is too low to compensate for battery leakage while using the present energy harvesting device.

CHAPTER 6

Testing Results and Discussion

6.1 Integrated Testing

The model was first tested in the laboratory, and then at the field where the sensor is designed to be used. The next two sections discuss the testing results for each part.

6.1.1 Laboratory Testing

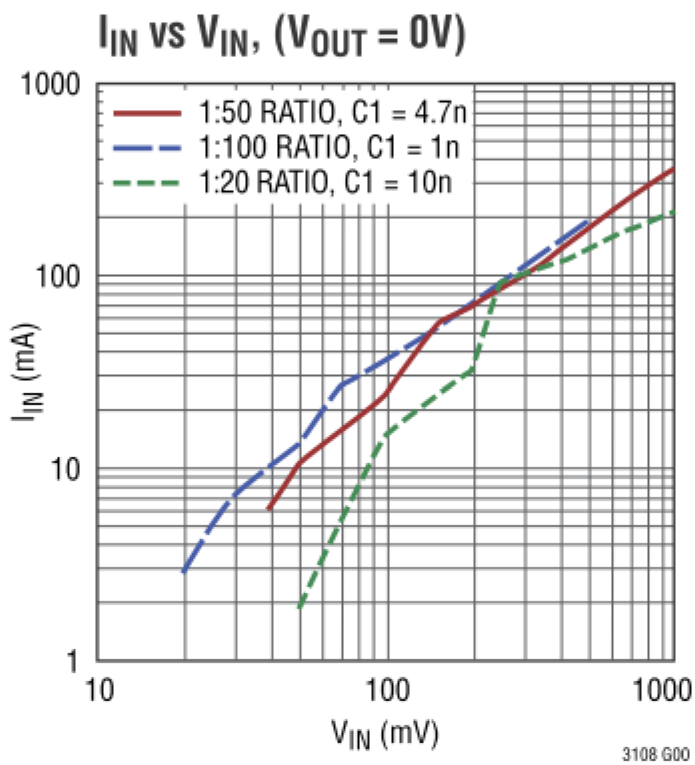
In the laboratory testing of the model, the plates of the TEGs were connected to aluminium plates that went into hot and cold liquids inside beakers. The output of the TEG was connected to the input of the power manager. The output capacitor in the PCB was connected to the input of the NPK sensor. Battery was removed from the sensor, and wires from the output capacitor were connected to the positive and negative terminals of the sensor. The 4 cm X 4 cm TEG succeeded in powering the sensor for a five degree temperature difference between the liquids. Table 6.1 shows the voltage to which the output capacitor charged up, when a 2 cm X 2 cm TEG was used with PCB designed to charge output capacitor to 5 V. It must be noted that the temperature difference is not between the plates of the TEG, but between the water stored in the beakers.

Table 6.1: Vout vs ΔT for 2 cm X 2 cm TEG

Temperature difference (degree Celcius)	**Open-circuit Voltage**	**Voltage with load**	**Output capacitor charge**
10	**26.4 mV**	**24.4 mV**	**4.60 V**
6	**19 mV**	**-**	**Fails to charge up**

Bigger TEGs will give higher voltages for the temperature differences shown in Table 6.1. Data from Figures 3.2 can be compared with Table 4.2 and Table 4.3 to determine the temperature difference required by each size of the TEG to successfully activate the power manager to charge the output capacitor.

A plot of Iin vs Vin is shown in Figure 6.1. Iin is 1 and 3 mA for 10 and 20 mV respectively. For this application a value of 30 mV is applicable, for which Iin is 6 mA. A TEG that has 0.5 or 1 Ohm internal resistance, will have a drop of 3 mV or 6 mV for an input of 30 mV respectively. This is not a great cause of concern when one is able to get 30 to 35 mV as the open circuit voltage of a TEG.



Source: [44]

Figure 6.1: Iin vs Vin to charge Vout

Bigger TEGs produce more voltage for a given temperature difference, and have a higher internal resistance. The presence of more thermocouples in a TEG adds up the emfs to produce a higher voltage, and adds up the internal resistances to offer a higher internal resistance. The overall effect is increased voltage availability on current draw-out, for bigger TEGs.

Once the output capacitor was charged, the sensor was switched ON. The needle of the meter was checked for deflection, and the output capacitor was checked to be discharged. Putting a resister to bring down the voltage to 1.5 V to the sensor ensured that the deflection stays within the limits on the display. The sensor needs to be recalibrated for accuracy.

6.1.2 Field Testing

The 4 cm X 4 cm TEG was used in the arrangement described in section 3.4. The aluminium plate connected to one side of the TEG went underground. Insulation tape was applied to the part of this aluminium plate that was exposed to the atmosphere. The other side of the TEG was connected to a similar aluminium plate that was exposed to the atmosphere. The TEG's output was connected to the input of Power Manager, which then was connected to the sensor.

Figure 6.2 shows the output capacitor charging when TEG was giving 22.7 mV on load by the power manager.

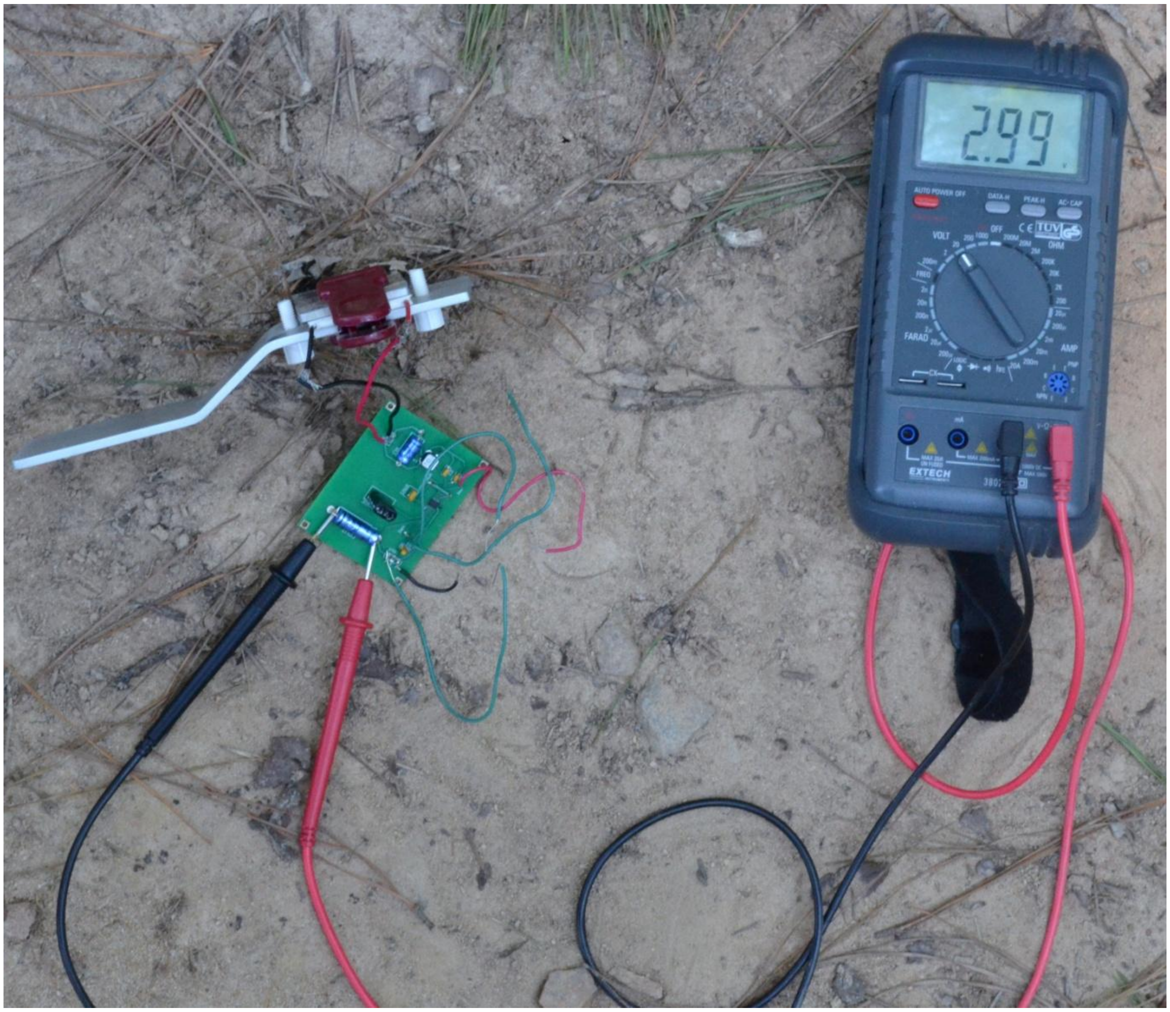


Figure 6.2: Storing electrical energy using ambient temperature gradient

Table 6.2 shows the metrics of the testing.

Table 6.2: Metrics of field testing

Ambient Temperature	**30.8 °C**
Soil Temperature	**24.6 °C**
OCV from TEG	**39 mV**
Voltage i/p from TEG on load	**21.7 mV**
Time to charge o/p capacitor	**230 s**

The model worked when the temperature difference was 6.2 °C. The TEG gave a steady open-circuit or no load voltage of 39 mV. This voltage dropped down to 21.7 mV when connected to the power manager. The output capacitor took less than four minutes to charge up for the power manager that was configured for an output of 3.3 V. When reconfigured to 2.35 V or when a new power manager is designed to charge to 1.5 V, the time to charge the output capacitor will be much lower. This will result in a sensor that has a higher duty-cycle of operation.

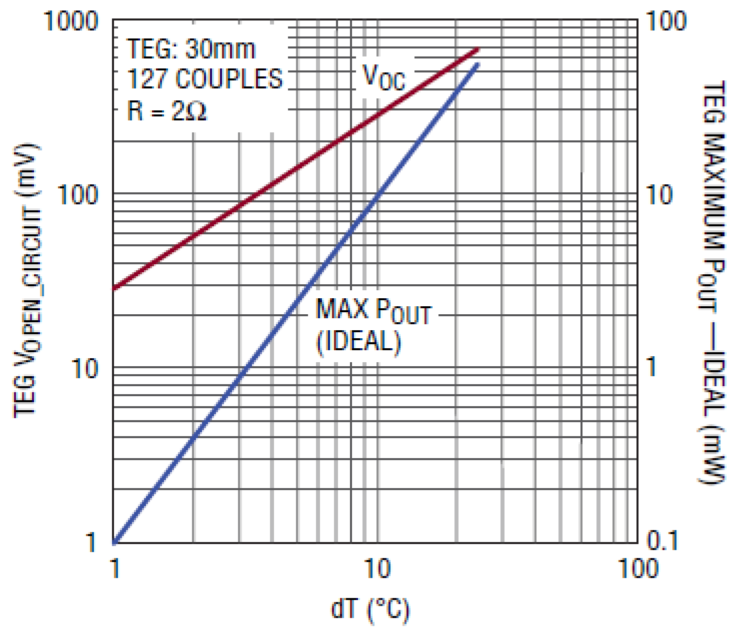
From the datasheet, the 4cm X 4cm TEG (part no: CP85438 from V-Infinity) has an internal resistance of 1.5 Ω. This implies that the power manager drew 11.5 mA.

The manual step in this experiment was to test the polarity of the voltage of the TEG before connection to the power manager inputs. The correct polarity can be guessed based on the ambient temperature and the past history of temperatures, or found using a thermometer.

When a model needs to be used commercially, the life of the energy harvesting device needs to be studied. A TEG was immersed in water for a few periods of time. Later on, the TEG always produced a constant voltage of 2 mV when connected to the PCB. This happened for all the cases where the open circuit voltage was from 10 mV to 100 mV. It is unclear what caused this. Problems like internal resistance changes cannot be deduced by measuring the open-circuit voltage since current drawn is very low. The energy harvesting device is designed to be on the ground in order to utilize the temperature difference to accumulate energy into a storage device Therefore, it must be made sure that the device is robust to rain, hail, heat, and wind exposure.

6.2 Power Analysis

TEGs have power densities of a few hundreds of microwatts for temperature differences of a few Kelvin. The graph below shows the power the TEG is capable of giving for different temperature differences between its plates.



Source: [44]

Figure 6.3: Power capability of 3 cm X 3 cm TEG

A 30 cm by 30 cm TEG gives 800 µW to 10 mW for temperature differences of 3 to 10 °C. Due to losses we don't get the exact temperature of the under-ground. A power input of 100 to 500 µW can be expected when using in the present application. This power goes into the power manager.

The power manager takes in higher currents with application of higher input voltages. Figure 6.1 shows the graph of input current versus input voltage. For a 20 mV input, we get 3 mA, which corresponds to 60 µW. For a 30 mV input and 7 mA, we get 210 µW. TEGs are very much capable of providing this power.

Some power is lost in the interconnects, transformer, capacitors and on-chip components. Power is also stored in the active components inside the LTC3108 chip, like the PGD signal logic. From the datasheet we see that the output capacitor charges to 3.3 V in roughly 110 seconds. A 210 µW input for 110 seconds is 23.1 mJ of energy. VSTORE, VLDO and VAUX store energy, apart from the output capacitor. When the 470 µF output capacitor is charged to 3.3 V, it stores 2.56 mJ of energy. If charged to 5 V using more energy from the TEG, the same capacitor stores 5.875 mJ of energy for use by the sensor.

When using LTC3018 to power a sensor that requires an input of 1.5 V, a resistor is required in series with the capacitor so that lower current is drawn by the sensor. Another DC-DC converter that steps down 5 or 3.3 V to 1.5 V is not necessary here due to the constant load of the sensor. A DC-DC step-down converter will also use more power than a resister since active components, diodes and resistors are used. Suppose 3.3 V needs to be dropped to 1.5 V, and the sensor requires 0.3 mA (at 1.5 V). A resistance value of 6 KΩ is required. The peak power consumption by the resister is 540 µW. This can be avoided if the power manager is designed to charge the output capacitor to 1.5 V. This would also reduce the time taken to charge the output capacitor, which in turn improves the duty cycle of operation of the sensor.

The PGD signal needs to be connected to the gate of a transistor to make sure that the sensor is powered only when the capacitor is fully charged. This transistor can consume 250 to 750 mW of power. A few hundreds of micro-Watts are consumed by the diode when the device is used to trickle charge a battery. These power levels are unacceptable considering that the output capacitor is charged only to µJ levels of energy. At a given time, either the transistor or the diode is used depending on the application. This additional power consumption can be reduced greatly if components are integrated within the chip depending on the application. In case of requirement to use for both applications, an additional pin can be created.

The sensor takes in 0.3 mA at 1.5 V, which corresponds to 450 µW. Agricultural sensors can be designed especially for energy harvesting which consume lesser power. By using the PGD signal along with a very low power sensor that draws µA, the duty cycle of operation of the sensor can be significantly increased. When a sensor draws very low currents, it is also possible to get the output capacitor of the power manager to simultaneously get back the charge consumed by the sensor, from the TEG. A continuous current can then be supplied if the power input exceeds the sum of the power consumption by the application (sensor), and the power loss within the power manager. The following text finds the approximate current that can be delivered by the power manager to the sensor, continuously.

From the earlier analysis, we find that an input power of 210 µW is required for 110 seconds, which is 23.1 mJ of energy, to charge the 470 µF output capacitor to 3.3 V. The energy stored in the output capacitor is 2.56 mJ. Based on experimental measurement of voltages at the capacitors, it was found that Caux (1 µF) had 1.25 V, Cstore (0.1 F) had 0.12

V and Cldo (2.2 µF) had 1.8 V. Note that these values can vary between experiments, and the leakage rates of capacitors. This corresponds to a total energy of 7.24 mJ. Rest of the energy supplied is either consumed or stored in active components within the power manager. This energy is 13.3 mJ, and for a 110 second period, corresponds to 120.91 µW of power. Subtracting this amount from the input power gives 89.09 µW. This means that the power consumption of the sensor can at most be 89.09 µW in order to ensure that the sensor can always remain on. For example, a 3.3 V input sensor can consume at most 27 µA of current. However, the current chip (LTC3018) is designed for pulsed current supply.

Figure 6.4 shows a plot of Ivout Vs Vin for a Vout of 4.5 V while using a 1:100 transformer. We see that as the input voltage supplied to the power manager is increased, we get higher output current capability. More details on the power manager can be found in the datasheet of LTC3018 [44].

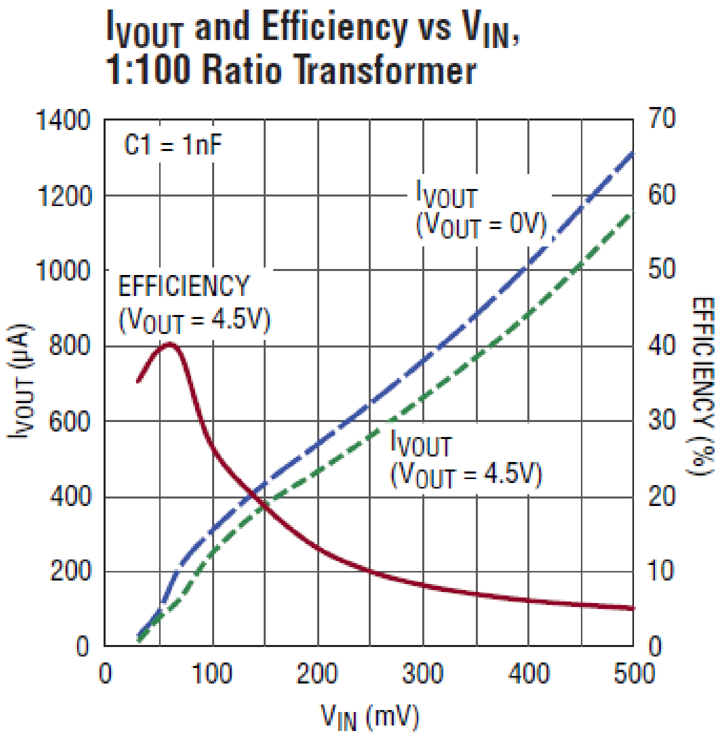


Figure 6.4: Iout Vs Vin for the power manager with 1:100 transformer

CHAPTER 7

Conclusions and Future Work

7.1 Summary

Soil-NPK indicator, PCB with the LTC3108, which is the power manager, and a TEG attached to thermal conducting plates, were integrated to test the ability to harvest thermal energy from the ground to power an agricultural sensor. The model was first tested to work in the laboratory where temperature difference was maintained using hot and cold water. The model was then successfully tested in the field where it is designed to be used. The constraints under which the model works were identified. The device was built using existing components and sensors, and characteristics required for better efficiency were identified. It is seen that the sensor would work for most part of the year, at least in Raleigh, NC.

Trickle charging of rechargeable batteries using the current device was analyzed for feasibility. It was found that the device can put the charge consumed by the sensor back into the battery. The concerns that need to be addressed are the reduction in battery life in terms of number of cycles of charging left off the battery, and the charge stoppage necessary in order not to over-charge. If the benefits of energy-harvesting are higher than the reduction in number of cycles from the life of the rechargeable battery, then one can go ahead and use the device for trickle charging. The rate of trickle charging required for both charging up a battery to full potential, and for keeping the battery full by compensating for the leakage, are higher than what the energy harvesting device can supply.

7.2 Key Contributions

The following are the main contributions of this thesis:

1. Successfully designed and tested a model that harvests thermal energy and powers a simple agricultural sensor by integrating a TEG with a thermal conductor, a power manager circuit, and an NPK/pH indicator.
2. Identified a set of approaches that could lead to better operation and real world suitability.
3. Captured the engineering issues that must be addressed in order to trickle charge a battery in a power harvesting application.

7.3 Future Work

For better duty cycle of operation of the sensor, a DC-DC converter that will give a 1.5 V output for an input of 10 mV would be desirable. Such a device will also facilitate the sensor to be powered for more times in a year.

Sensors need to be built for the purpose of energy harvesting. They can be optimized for being operated at low powers. For example, a sensor with an input voltage of 1 to 1.5 V, and a low current requirement (µA range), would consume little power (µW range). Using ISFETs and creating a circuitry to make sure that the input voltage to the sensor is within regulation with the help of PGD signal from the LTC3018 is an option. [37] is a good source for understanding of ion selective electrodes. Chapter 5 of the book deals with the principles of potentiometric measurements and ion selective electrodes.

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