ENERGY HARVESTING ROUTING ALGORITHM FOR RFID SENSOR TRANSPONDER

SHALINI SELVAM

A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Mechanical)

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature	:	
Name	:	Shalini Selvam
ID No.	:	18UEM00859
Date	:	09th May 2019

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"ENERGY HARVESTING ROUTING ALGORITHM FOR RFID SENSOR TRANSPONDER"** was prepared by **SHALINI A/P SELVAM** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Electronic Systems) at Universiti Tunku Abdul Rahman.

Approved by,

Signature	:	
Supervisor	:	Dr. Khaw Mei Kum (Alice)
Date	:	09th May 2019

Signature	:	
Co-Supervisor	:	
Date	:	

ABSTRACT

Energy harvesting is a process of capturing an amount of energy from one or more sources such as solar energy, light energy, thermal energy, wind energy and kinetic energy. The main objectives of this project is to develop thermal energy, RF and piezo energy harvester models; combine output of these 3 harvesters into one output. Thermal energy, RF and piezo energy harvesters are designed with a voltage booster for each of the harvester. An output voltage of 380mV, 350mV and 350mV are obtained for thermal energy, RF and piezo energy harvesters respectively. A multi-source energy harvester is modelled with input of thermal, RF and piezo energy harvester circuits. The proposed designed combine the output from these 3 different energy harvesters into one output with aid of voltage booster. The proposed design is simulated and data analysed by using Synopsis EDA tool. The maximum output voltage achieved with design is 0.75V. Harvested energy from proposed algorithm is insufficient to power up the RFID transponder as it needs minimum input voltage of 2.7V. Thus, this proposed algorithm can be improved to increase the harvested output voltage up to 2.7V minimum in future work.

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LIST OF SYMBOLS / ABBREVIATIONS

RF	Radio Frequency
RFID	Radio Frequency Identification
DC	Direct Current
IC	Integrated Circuit
FEA	Finite Element Analysis
TEM	Thermoelectric Module
ADC	Analog to Digital Converter
HPMU	Hybrid Power Management Unit
EEMU	Excess Energy Management Unit
CCO	Current Controlled Oscillator
CF	Current Feeder
VFG	Voltage Reference Generator
VREF	Reference Voltage
VREC	Output Voltage
LDO	Low Drop-Out
V_{TEG}	Source Voltage
R_{TEG}	Internal Resistance
C_{IN}	Decoupling Capacitor
M_1, M_2	Transistors
SW1-SW4	Switch Matrix
C_{STO}	Storage Capacitor

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CHAPTER 1

INTRODUCTION

1.1 Background of the Project

In recent years, power electronic devices have seen tremendous growth and being traditional applications in the area of information technology, factories, home appliance, transportations and power systems. The primary function of the power electronic devices is to control and transform electric energy in term of voltage, current, waveform and frequency. But in current trend of today, technology development results in shrinking size of electronic components. Thus, the focus has shifted from low power circuitry to small self-powered in standalone chip that have the ability to functional as battery-less chip. This will add advantages for the devices functioning long period and not ease accessible for maintenance to change batteries; save battery replacement and servicing cost. However, limitation in power reduces a number of functions in chip. For instance, conventional battery-less (Radio Frequency identification) RFID sensor transponder draws (Radio Frequency) RF energy from the reader to power the transponder can only function for limited distances. Thus, the RFID sensors will not be able to function for continuous monitoring, data collection and transmission as the acquired power will be insufficient. Therefore, battery-less wireless communication systems are focused with energy harvesting technology integration.

1.2 Problem Statement

Energy harvesting is a process of capturing an amount of energy from one or more sources such as solar energy, light energy, thermal energy, wind energy and kinetic energy. These form of energy will be stored and accumulated for later use. Decreasing waste stream by reducing the flow of replacement of battery into landfills proofs that energy harvesting technology is environmental friendly. There are many researches carried out to design the integrated circuit (IC) of multiple energy harvesting strategies and power management unit to manage the sources. Energy from the sources is time and environmental dependent. High power density is achievable by providing consistent voltage level to the circuitry. Thus, an energy harvesting routing algorithm to allocate different power converters that vary with time is essential.

1.3 Aims and Objectives

This project will focus on the algorithm establishment to allocate different power converter with time in the power management unit. As mentioned earlier, multi-source energy harvester approach will bring the electronic world towards self-powered standalone chips technology. Thus, this project has main objectives as listed below:-

- To study the approaches taken previously and identify the minimum energy can be harvest from thermal, RF and piezo energy.
- To design electrical models for thermal, RF and piezo energy harvesting sources.
- To develop an algorithm to combine the harvested energy from thermal, RF and piezo energy simultaneously.

RFID sensor transponders are deployed in the environment and they are the best candidates to capture the energy from environment and stored for power up the standalone battery-less wireless systems. The whole sensor network will be configured as a computer system that can be programmed to achieve the main objective of this project. Thus, the RFID sensor transponder will be able to sense the energy from source continuously for a long period of time, stored and accumulate the energy to power up the device even in inharmonious environment. It will be desirable for the critical automation industries, namely identification of harmful agents, continuous patient monitoring system in medical line and infrastructure and object monitoring.

1.4 Scope of the Project

The primary objectives of this research project are listed as below:

- To design thermal energy harvester circuit.
- To design RF energy harvester circuit.
- To design piezo energy harvester circuit.
- To combine the output from thermal, RF and piezo energy harvester.
- Synopsys EDA tool is chosen for the energy harvester algorithm development.

Energy from thermal, RF and piezo energy will be extracted and regulated to combine in second level model. Synopsys EDA tool will be used to develop the algorithm to achieve the objectives of this project.

1.5 Outline of the Report

This research project report is divided into five main chapters. The first chapter explains briefly the introduction part. This section includes the background study, problem statement, primary aims and objectives, and scopes of this project. Lastly, the outline of the report is explained in this section as well.

Chapter 2 is literature review that contains detailed background study about the harvesting energy from thermal, RF, thermal energy and also from multi-sources simultaneously. This section also includes the advantages and disadvantages of the techniques that carried out in earlier. This chapter will show the clear picture of the project on how the every energy is being harvested.

For the third chapter, methodology is written to explain every single approach and method that are carried out to achieve the objectives of this project. It also includes the details on block diagram of the proposed design, components and components parameters used in this project.

Chapter 4 is all about the discussion on results. The results obtained via Synopsis EDA tool are presented in the form of figures. The analysis was made from the result obtained.

Chapter 5 is final conclusion. This section will briefly conclude the observations, advantages and disadvantages, findings and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Harvesting Energy

The current trend of today's low-power electronics is self-sustainability. Electronic devices has been manufactured as a self-powered in standalone chip rather than as a low-power circuitry. However, limitation in power reduces the number of functions in a chip. Thus, the need of energy harvesting technology integration with the electronic devices is increased. This will enhance the ability of electronic devices to function independent of recharging and replacing of batteries.

Energy harvesting is a process of collecting energy from external sources such as solar energy, thermal energy, wind energy and light energy, accumulating and storing them for later use such as to charge mobile phone and in RFID applications (Nalini et al., 2017). This energy harvesting technology integration with low-power electronic devices will be alternative to a conventional battery (Lin et al., 2017). Majority of the low-power portable electronics and wireless sensors will be benefited from this development.

2.2 Piezo Energy Harvesting

(Kirubaveni and Radha, 2016) explained the techniques used to extract the vibration energy from cantilever structure with the piezoelectric material and converts it into electrical energy for the system usage. Vibration energy harvest module consists of energy harvester, rectification circuit, boost circuit and battery as shown in Figure 2.1 below. Primary function of the rectification circuit and boost circuit are to convert the vibration energy into DC output and to enhance the DC output of rectifier circuit respectively. This model provides maximum output voltage of 3.29V.

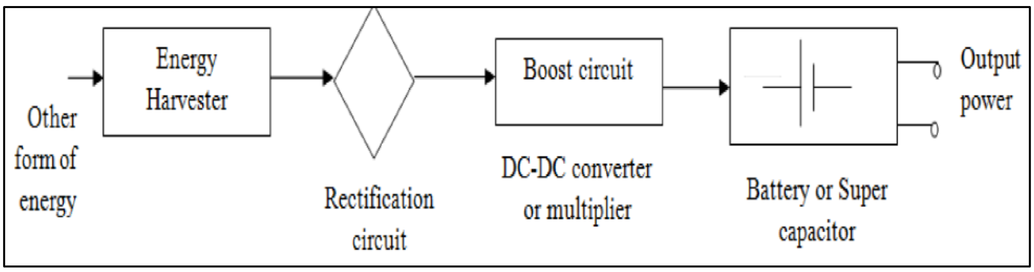

Figure 2.1: Vibration Energy Harvesting System Module

A design was conducted by (Balguvhar and Bhalla, 2018), which investigated the piezo energy harvesting low frequency bridge vibrations. The main limitation of this energy harvesting method is the output voltage from piezo energy harvester is cannot be used in electronic devices directly. Regulation of output voltage by interference circuit is necessary to condition the electrical energy. The one issue that still need to be solved in this work is the high power dissipation. The maximum output voltage harvested in this work is 4V. The maximum power harvested can be modelled by equation (2.1).

$$P_h = \frac{E_c}{T_c} \qquad (2.1)$$

where,

P_h = Harvested power

E_c = Charged Energy

T_c = Charged Period

Theoretically, maximum output voltage of 5.99V can be obtained (Jayarathne et al., 2018). This has been proven by using Finite Element Analysis (FEA). But, average output voltage value of 3.65V is obtained in this research by using motor bike as a source of vibration energy. Researcher discussed on maximizing the output voltage by increasing the length of beam and configuration of bimorph in sensor even with more displacement if motor bike, maximum output voltage of 5.99V is achieved.

2.3 Thermal Energy Harvesting

Thermal energy can be harvested from parts of human body such as wrist and palm (Wong and Dahari, 2015). (Mitcheson, 2010) have explored the option for energy harvesting from human body for harvester-powered body sensor network. Researcher proved that thermal and kinetic energy harvesting from human body especially when the subject is walking or running. A higher power density is able to achieve. This technique adds advantages for miniature biomedical devices to power up the bio-sensors. The maximum output voltage of 2.9V and 2.47V are measured at voltage booster and load respectively.

Thermal energy harvesting module consists of thermoelectric module (TEM), voltage booster and load (Wong and Dahari, 2015). Electricity is generated when temperature difference is present in the TEM and the output voltage level is boosted by using voltage booster. In this paper, a voltage booster IC (LTC3108) is used as it is able to manage the changing and regulation of multiple outputs. Figure 2.2 shows the thermal energy harvesting module. Output power generated during walking and running are compared. Maximum output power of 20μW/cm^3 and 10μW/cm^3 are harvested from heat generated during running and walking respectively.

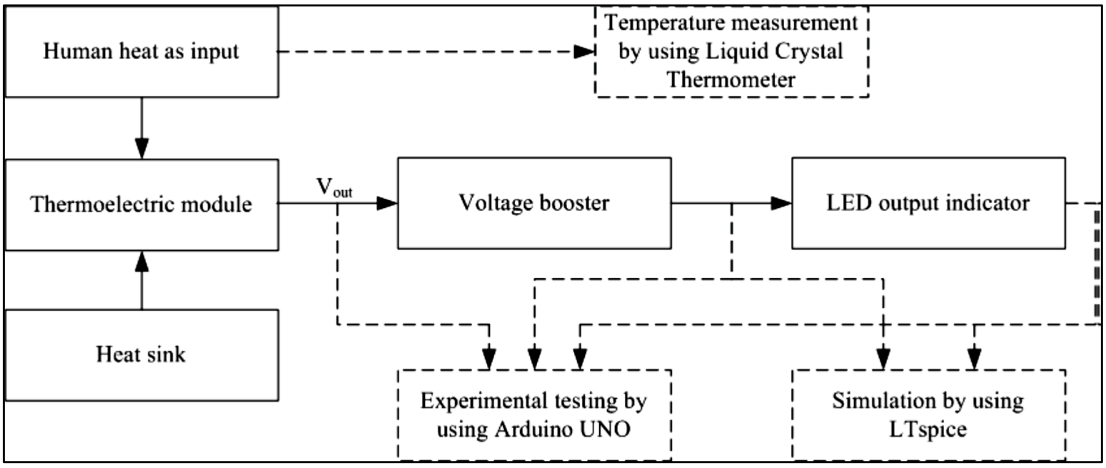

Figure 2.2: Block Diagram for Thermal Energy Harvesting

Energy harvesting from kinetic energy and thermal is difficult to be compared to the energy harvesting from vibration and temperature rich environment (Mitcheson, 2010). Whereas, the main constraints of the proposed method also has been discussed in this paper. The main limitation of the proposed method is lesser frequency of human body motion. Moreover, the gradient between human body and environment temperature is very difficult to handle.

The potential thermal energy harvesting from mobile applications such as laptop and mobiles are discovered (Mongia and Abdelmoneum, 2010). Expected power range of 300mW to 600mW can be harvested from these applications. This maximum amount of harvested energy possible to extend the battery life of a laptop of 65W-hr up to 94minutes.

2.4 Radio Frequency Energy Harvesting

Energy harvesting from RF signal model with output voltage range of 0.6 – 1V developed as shown in Figure 2.2 (Nalini et al., 2017). RF energy harvester model consists of an antenna and impedance matching circuit, rectifier circuit, voltage multiplier circuit and harvested energy storage or load (Nalini et al., 2017), (Cansiz et al., 2019).

Antenna is used to collect the RF signal in the range of 935 – 960MHz from external sources such as mobile phone and the signal is then impedance matched to remove the noises in the load. There are various matching impedance matching circuits, namely Type Π, Type L and Type T (Cansiz et al., 2019). Each type of impedance matching circuit has its own advantage. Type Π has wider matching impedance network, Type L has higher efficiency and Type T improves output voltage levels.

Rectifier circuit converts the RF signal into DC voltage with minimal voltage drop. Whereas the voltage multiplier circuit act as a DC-DC voltage converter circuit and enhance the DC output from rectifier circuit. The voltage is used to display the LCD which is connected to antenna through ADC and microcontroller. The voltage is again boosted by chopper circuit and stored by ultra-thin capacitor (Nalini et al., 2017). The voltage is then switched to load by relay circuit when the battery energized up to 12V. Supercapacitor can be used to replace rechargeable battery to store the harvested energy (Cansiz et al., 2019). The voltage level of battery is constantly monitored by voltage divider circuit in the LCD. Advantage of this model is able to harvest RF energy through electrical energy conversion. Whereas, the major limitation of this model is it only produces output voltage range of 1 – 2V with RF of 935-960MHz range.

(Sun et al., 2017) proposed new concept on fully-integrated hybrid power management units (HPMU) as shown in Figure 2.2. The design consists of 2 important class blocks, namely power routing unit and excess energy management unit (EEMU). EEMU consists of a voltage reference generator (VFG), rectifier, current controlled oscillator (CCO) current feeder (CF), and charge pump. All the elements in the EEMU have plays their own function. VFG generates reference voltage VREF for the system which independent on the VREF. Whereas, the rectifier act as an input signal receiver and convert the received RF signal into DC output voltage, VREC. Current feeder controls the current amount supplied to the CCO. Then, the CCO and charge pump pulls the voltage from VREF to regulate the VREC to a LDO desired voltage.

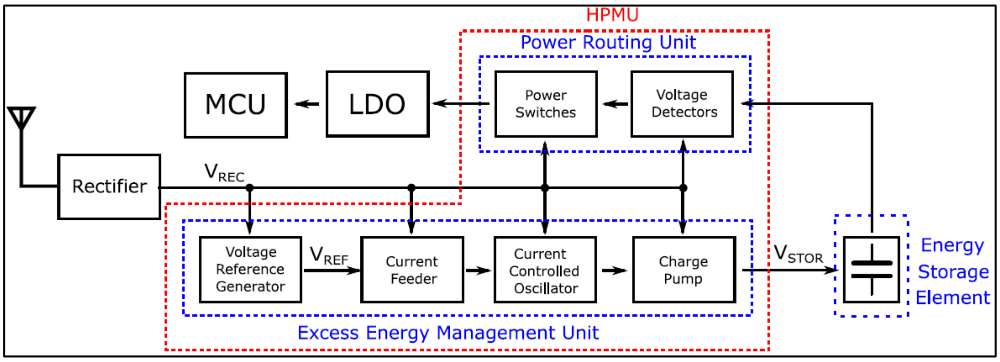

Figure 2.3: Block Diagram of Fully Integrated HPMU

Lastly for EEMU, the CCO drives the charge pump for external power storage. Whereas, PRU consists of power switches and voltage detector and function as a router to route either the VREC or stored energy to power the load, LDO. In this proposed design, the power routing is depend on 2 criteria. The power is transferred to load, if the VREC is equal to 2.5V or more than stored energy to prevent sudden power loss. Or else system will be switched off, if the VREC is less than 1V (Sun et al., 2017).

2.5 Multi-Source Energy Harvesting

While energy harvesting from single energy source are developed, harvesting energy from various sources simultaneously also being developed in recent years (Le et al., 2017). The main advantages of the multisource energy harvesting approach are able to salvage more energy from internal and external environment and able to increase self-independency of the electronic system. For an example, electronic system may be turned-off as power in single source energy harvesting approach may depleted when source of energy is not available. Whereas, in the multi-source energy harvesting approach continuous power supply is achievable as alternative source of energy is presents (Li et al., 2018), (Carli et al., 2011). There are 3 primary challenges in achieving multi source energy harvesting designs which includes: 1) 20mV to 5V range of input voltages; 2) difference in maximum extraction of power due to ohms to kilo ohms range of harvester impedances; 3) sizing of components in circuit (Heidari et al., 2015).

In the early decades, single path architecture is developed to combine various outputs from multiple harvester sources (Ferry et al., 2013). This method contains either a battery or a supercapacitor as an energy storage. The main disadvantage of the explained approach is only one harvested energy can be utilized while other will be wasted and cold booting issue. Thus, dual path architecture is developed with 2 energy storages, namely primary and secondary storage (Le et al., 2017). In this approach, wind and solar energy harvesting is utilized in wireless sensor node by using plug-in harvesting system that developed based on dual path architecture with LTC3108. This approaches proves that the cold booting issue resolved and long period of system operation. LTC3108 is used as it is able to manage the charging and regulation of the multiple outputs (Wong and Dahari, 2015) and able to boost the lower energy into higher output levels (Le et al., 2017).

A design of multi-source energy harvesting is proposed by utilizing thermal energy, solar energy and vibration energy. Each of the energies delivers maximum output power of 2.9mW, 30mW and 2.61mW respectively (Li et al., 2018). Figure 2.4 represented block diagram of the architecture of proposed design. Negative voltage converter in the design used for only piezoelectric input as it generates AC signal and need to be rectified. The function of buck converters are to regulate the voltages to 3.3V and 5V. Whereas, Texas Instrument IC, BQ25504 is also a low power boost converter and it is used for impedance matching purpose. The function of energy level indicator is this design is to sense the voltage stored in the capacitor.

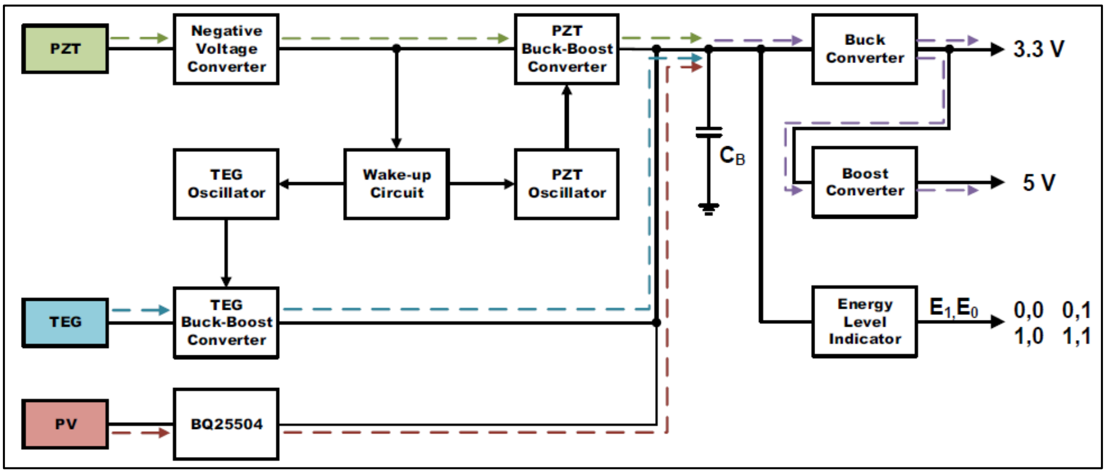

Figure 2.4: Block Diagram of Multi-Source Energy Harvester

RF, thermal and solar energy harvesting circuits are developed independently and setup to form as a multi-source energy harvester circuit by regulating the output voltage from each energy harvester to 3.3V (Davut et al., 2017). Each harvester output is connected to supercapacitor through the Zener diode to ensure one direction of current flow. This approach is able to store 2.4V as voltage drop across the Zener diode is 0.9V. The same energy harvester sources are utilized to increase the life time of power supply up to 22% in sensory glove system (Stomelli et al., 2018).

A power management unit (PMU) architecture with thermal and vibration energy harvesting is presented (Alhawari et al., 2016). The load used in this paper is ECG processor. Since the functions of ECG processor are ECG signal analysis and ventricular arrhythmia (VA) prediction, it requires multiple voltage levels. Thus, a PMU is utilized in this presented architecture for different signal generations to enable and disable the processor based on the energy level available.

In (Davut et al., 2017), several approaches on harvester connection is discussed. DC output of each harvester circuit can be combined in serial, parallel and cascaded forms to obtain maximum output power. The advantages and disadvantages of the serial and parallel approaches are summarized in the table below.

Table 2.1: Advantages and Disadvantages of Serial and Parallel Harvester Connection

Approach type	Advantages	Disadvantages
Serial connection	• Able to achieve high voltage output • Voltage booster not required • Easy to reach voltage sensitivity	• Sharing same current and may lead to deliver maximum output power • Reduces robustness of energy harvester
Parallel connection	• Allows to run each DC output at maximum level • Sources able to feed independently • Able to prevent outage of energy harvester system • Enhances robustness of energy harvester system	• DC output of source need to be maintain at same level to prevent dominancy of high level voltage output

2.6 Summary

Energy harvesting approach is very important and challenging in current generation. There are several approaches has been developed by many researchers. The main topology of the design in decoupling, impedance matching, voltage rectification and amplification. The main challenge in this field is the step towards multi-source harvesting simultaneously.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

Figure 3.1 represents the block diagram for the overall multi-source energy harvester design proposed in this paper. This design consists of RF, piezo and thermal energy harvesting circuits. These are act as input for the prototype whereas the voltage stored in capacitor taken as the output of this prototype. Prior to the simulation and analysis, HSpice-Synopsys EDA tool is used.

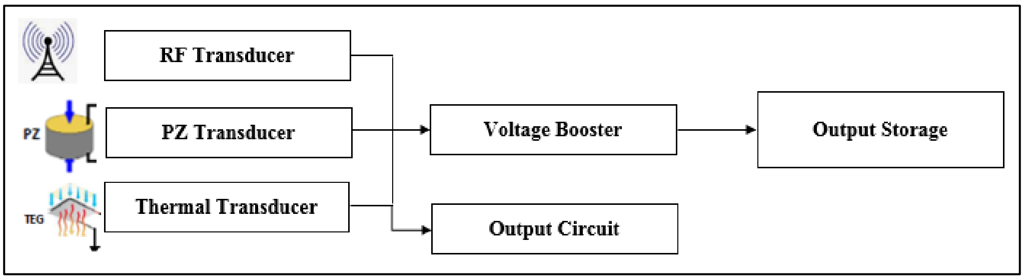

Figure 3.1: Block Diagram for Proposed Design

3.2 Thermal Energy Harvesting

Heat dissipation between 2 surfaces triggers electricity generation. Therefore, thermoelectric generator is required to coverts the temperature difference between hot and cold plate into electrical energy. An equivalent electrical model for thermoelectric transducer module is utilized in this proposed prototype. Figure 3.2 represents the thermal harvester architecture.

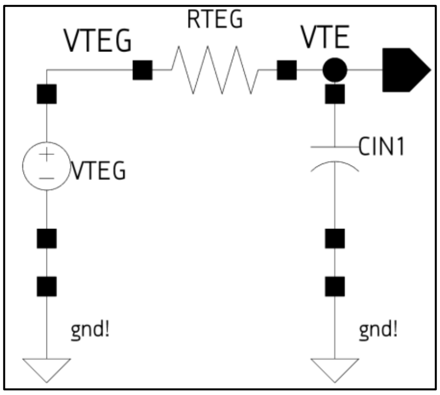

Figure 3.2: Thermal Harvester Schematic

This module characterized with a source voltage, V_{TEG} placed in series with a resistance, $R_{TEG.}$ This resistance represents the internal resistance of the transducer. The output terminal is connected with decoupling capacitor, C_{IN} to filter the fluctuation and noise presents in the input signal.

3.3 RF and Piezo Energy Harvesting

RF and piezo energies are active energy sources. Thus, rectifiers are implemented in the harvester designs to rectify the AC signal to desired DC voltage levels. Figure 3.3 shows the schematic design of RF and piezo energy transducers. In the proposed design, 2 diode connected transistors, M_1 and M_2 are utilized as a function of rectifier. In order to reduce the noises in the input signal, decoupling capacitor, C_{IN} is implemented in parallel with output terminal.

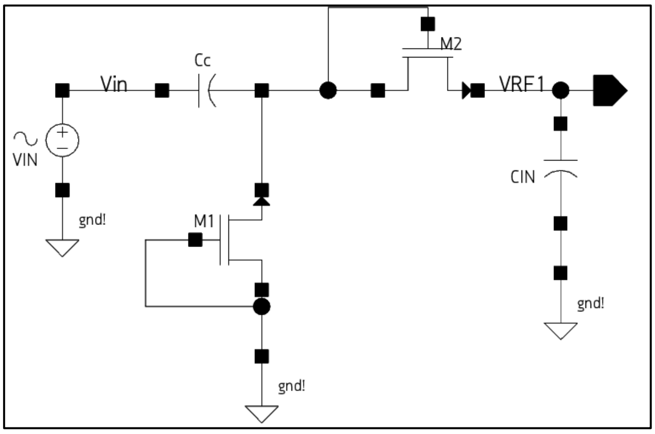

Figure 3.3: Energy Harvester Schematic for RF and Piezo Energy

3.4 Multi-Source Power Energy Harvesting

Equivalent electrical model for the proposed multi-source power harvesting system is shown in figure 3.4. Thermal energy, RF and piezo energy harvester discussed earlier are connected in parallel to the output terminal. Switch matrix of SW1, SW2, SW3 and SW4 are used to isolate the input sources and power stage. The function of SW4 is to ensure the system operating in 2 different mode of operations, namely mode of harvesting and mode of regulation. Harvesting mode and regulating modes are configured as electrical energy extraction from RF, thermal and piezo energies and storing the electrical energy in storage capacitor, C_{STO} respectively.

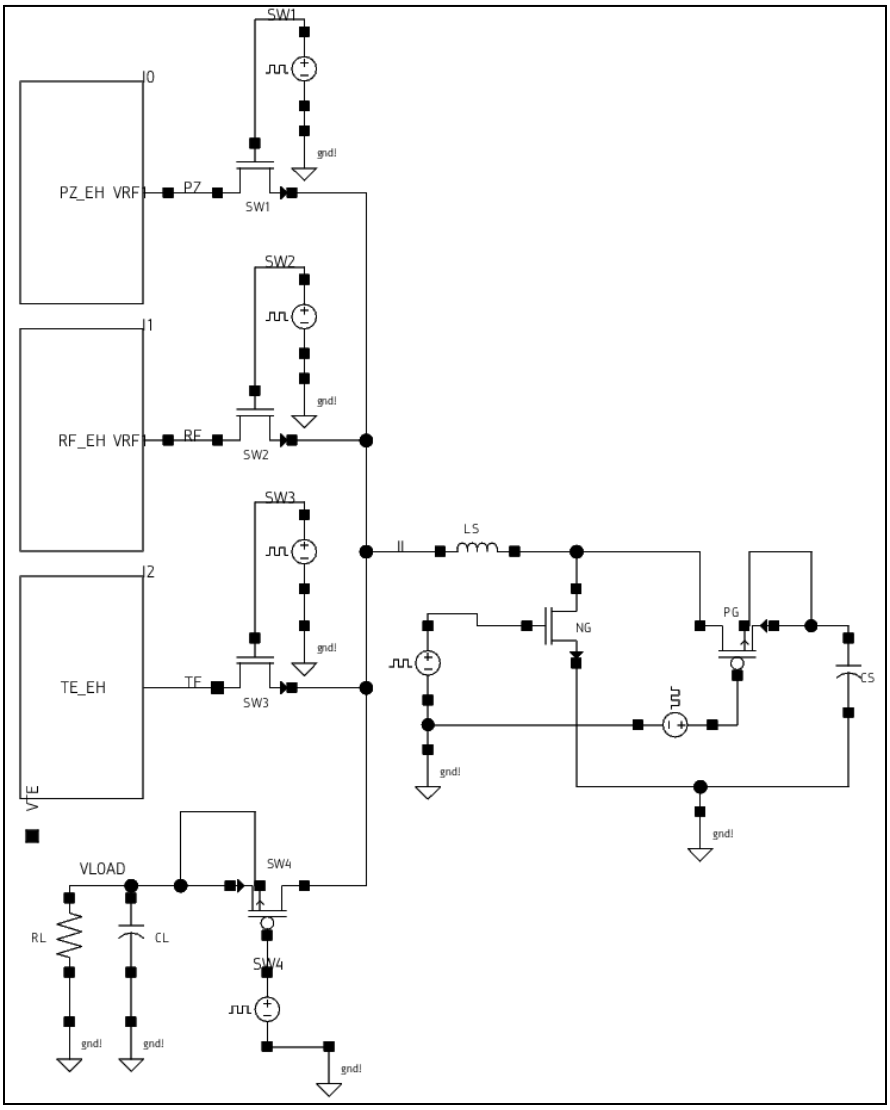

Figure 3.4: Multi-source Energy Harvesting Design

Table 3.1 summarizes the design parameters utilized in this proposed design. Whereas, Table 3.2 summarizes all the parameters of RF, thermal and piezo energy harvester designs.

Table 3.1: Design Parameter for Proposed Design

Component	Values
Storage Capacitor, C_{STO}	2.6 mF
Internal Resistance, R_{TEG}	~3Ω
Input Capacitor, C_{IN1}; C_{IN2}; C_{IN3}	4.7 pF, 22µF, 12µF
Load Capacitor, C_{LOAD}	~47 µF
Power Inductor, L_{STO}	8.2 µH

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The objective of this project is to design a model for thermal, RF and piezo energy harvesting. Then, to combine the output of these 3 harvesters into a stable 1 output via voltage booster. In this project, the way to attain the objective of this project is via designing, simulation and data analysis. This section holds an important role of answering any doubt regarding or system of the project. Any discovery or outcome are discussed and analysed.

4.2 Thermal Energy Harvesting

Figure 4.1 shows the result of voltage generated by thermal harvesting equivalent circuit when it is connected to voltage booster circuit.

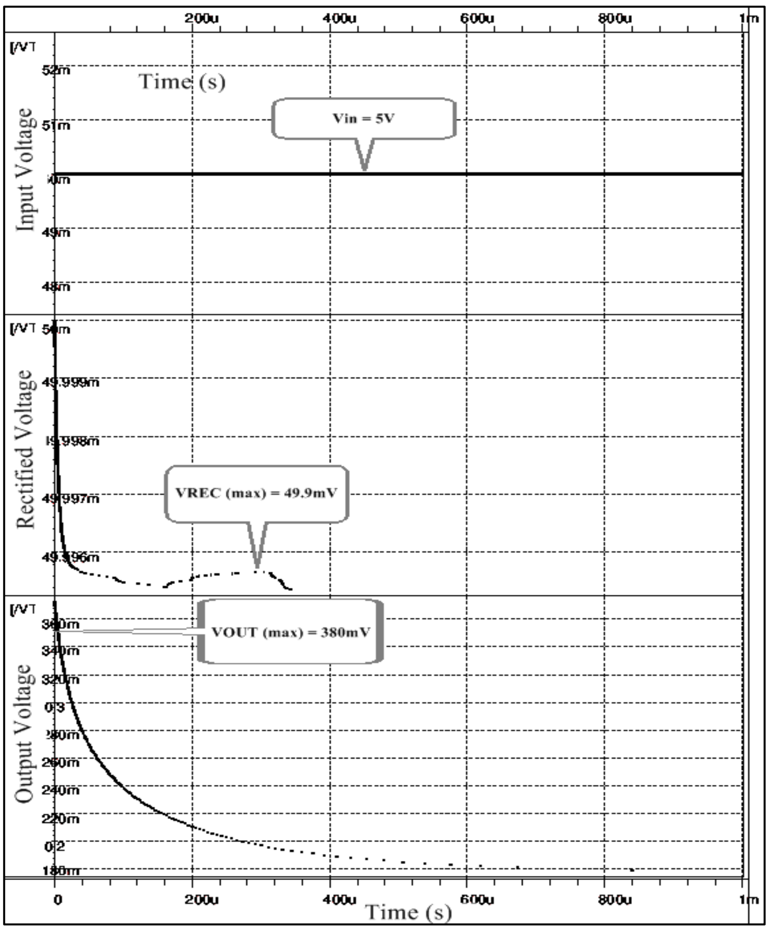

Figure 4.1: Simulation Waveform for Thermal Energy Harvester

Equivalent electrical model for thermal can be characterized with source voltage on 50 to 300mV for temperature range of 2 to 12°. Thus, input voltage, V_{TEG} of 50mV is applied to the circuit and obtained almost output voltage of 49.9mV is obtained. Voltage booster is very important to amplify the voltage harvested initially from thermal module. In this design, 49.9mV voltage is rectified to 373mV.

4.3 RF and Piezo Energy Harvesting

The RF energy harvester design provide output voltage of 200µV with input voltage of 2V. In order to represent the RF energy source, frequency of 2.4GHz is fixed to the input source. The output voltage from RF energy harvester in connected to voltage booster circuit and obtained final output voltage of 350mV. Figure 4.2 shows the output waveform for RF energy harvester design simulated with software.

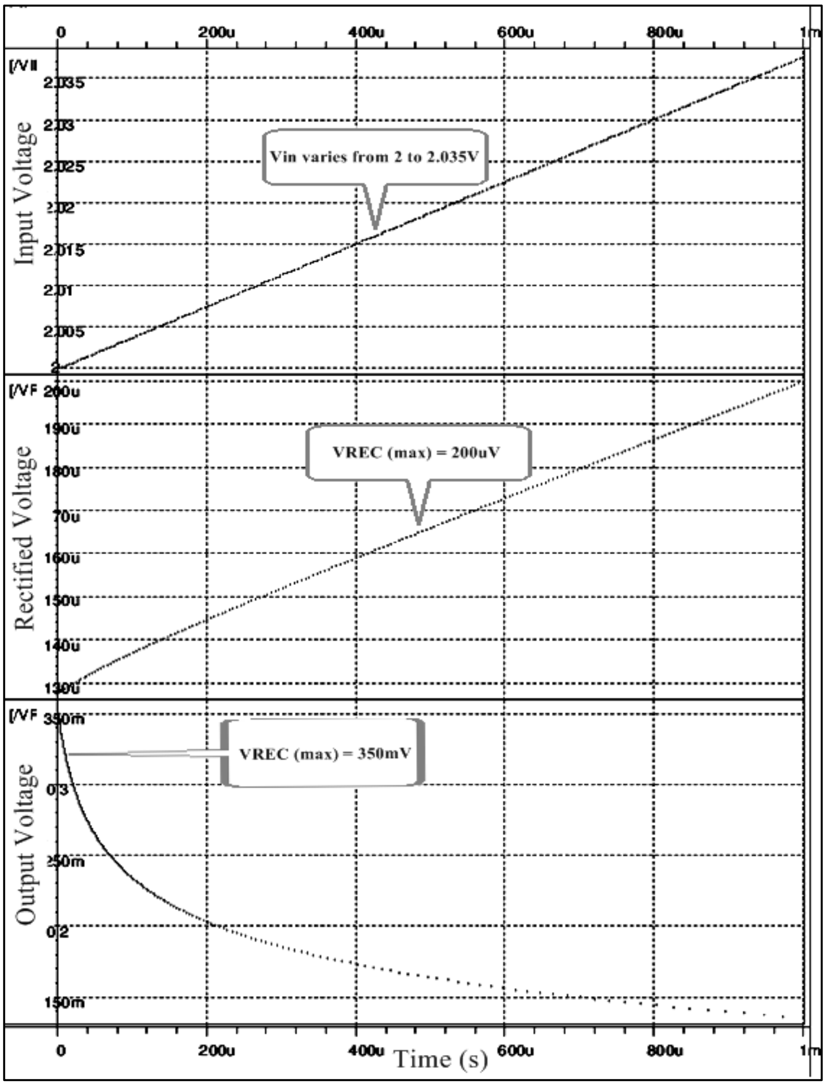

Figure 4.2: Simulation Waveform for RF Energy Harvester

The same circuit is applied to PZ energy harvester design with input frequency of 2Hz and obtained output voltage of 130µV with input voltage of 0.6V. Figure 4.3 shows the output waveform for PZ energy harvester design simulated with software. The maximum final output for the proposed design is 350mV, after passed through voltage booster circuit.

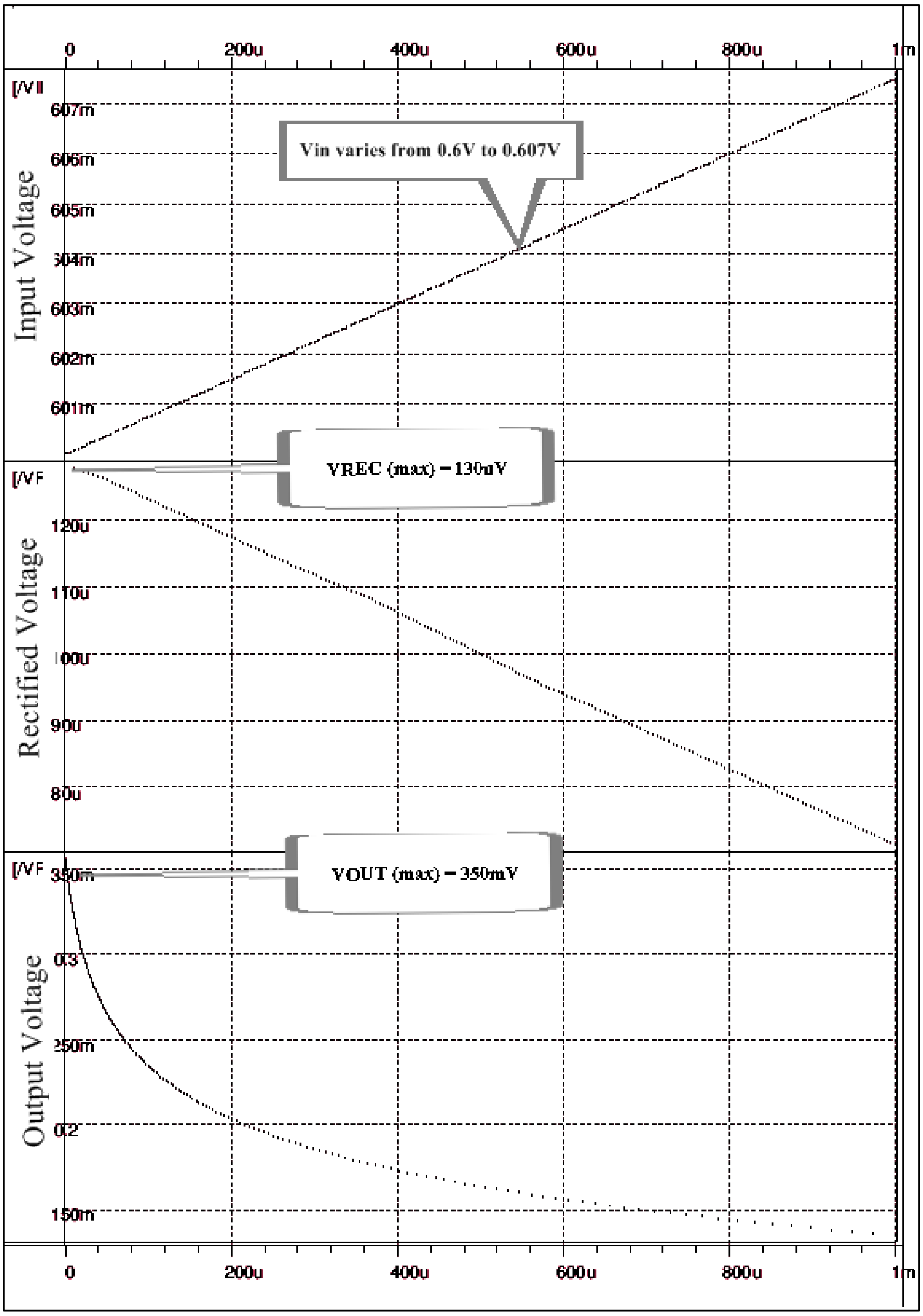

Figure 4.3: Simulation Waveform for PZ Energy Harvester

4.4 Multi-Source Energy Harvesting

The simulated results for proposed multi-input energy harvester in this paper is represented in Figure 4.4. Storage capacitor with a value of 2.6mF is used in this design to remain the output voltage stable for 0.3s. Maximum output voltage at load can be achieved with this design is 0.75V. Output from each harvester is regulated to 1.5V and stored at storage capacitor, C_{STO}. The maximum voltage stored at capacitor before supply to load is 1.38V.

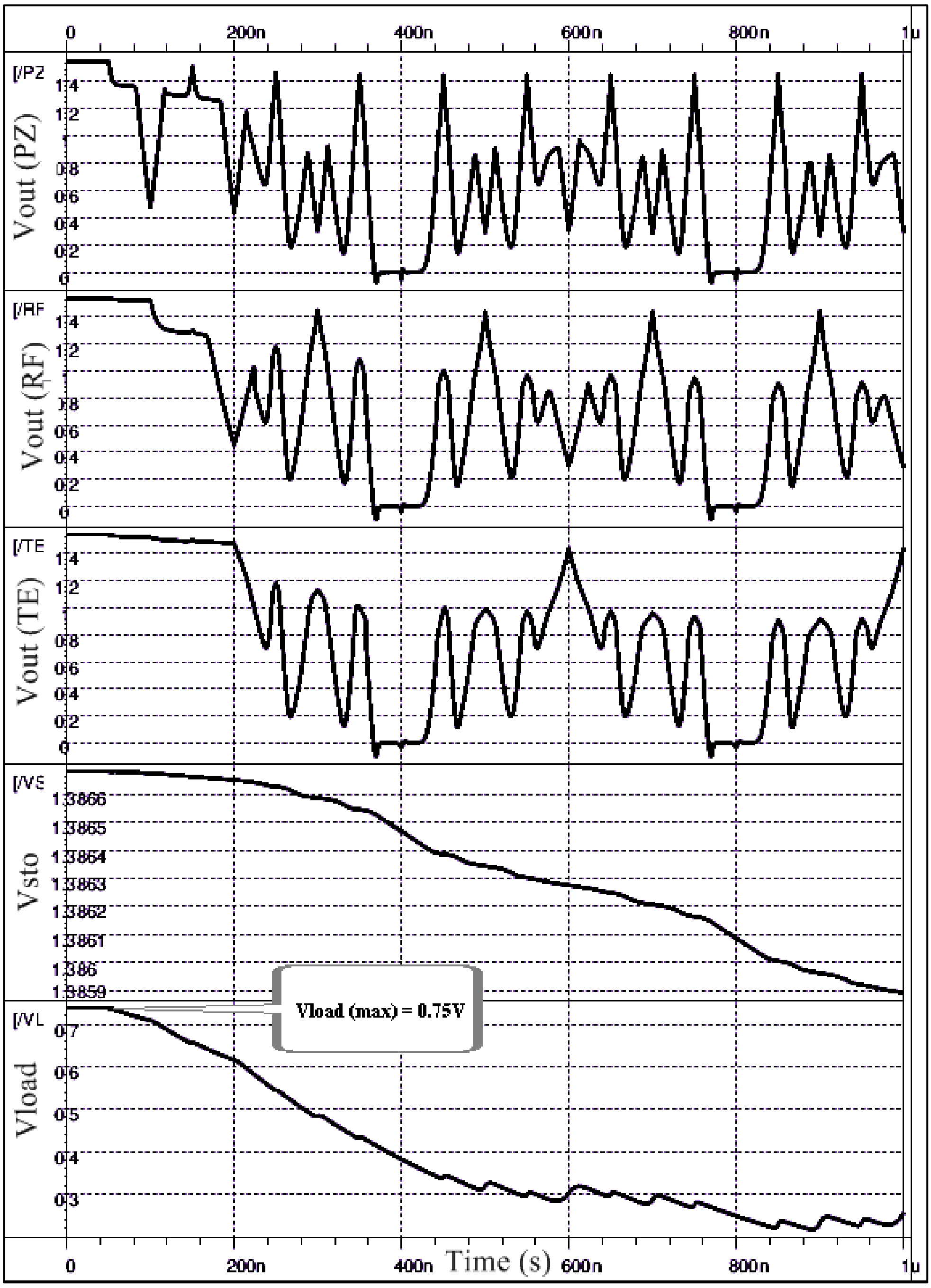

Figure 4.4: Simulation Waveform for Multi-Source Energy Harvester

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In the end of this project, the conclusion that can be made is this project has achieved the project objectives to design multi-source input energy harvester. The simulation result for multi-source energy harvesting shows the design functions properly during simulation. The proposed design in developed with 3 input sources, namely thermal energy, RF and piezo energy. All these 3 equivalent DC models are multi-source power converter designed. It deals with thermoelectric, piezoelectric and RF energy simultaneously. The proposed design ensures maximum voltage extraction of 20µV.

5.2 Recommendations for future work

The limitation observed from the proposed model is the amount of energy harvested is only 0.75V. Based on the RFID transponder datasheet, minimum voltage input required is 2.7V and proposed method only able to stored voltage of 1.38V. Thus, the harvested energy from proposed model is insufficient to power up the RFID transponder. The future study should be done for this project to find the way to increase the harvested voltage to minimum of 2.7V. This may lead to more challenge as they have wide range of voltage sources and impedances. The main focus of this project is to produce electricity and save the environment. This project is carried out as prices of global energy increasing significantly due to limitation of power supply resources. With an alternative solution, this idea on renewable sources can lead to cut cost by moving towards battery-less technology. This approach towards renewable sources can reduce the cost of maintenance for electronic devices by changing batteries and also to have non-stop function of devices.

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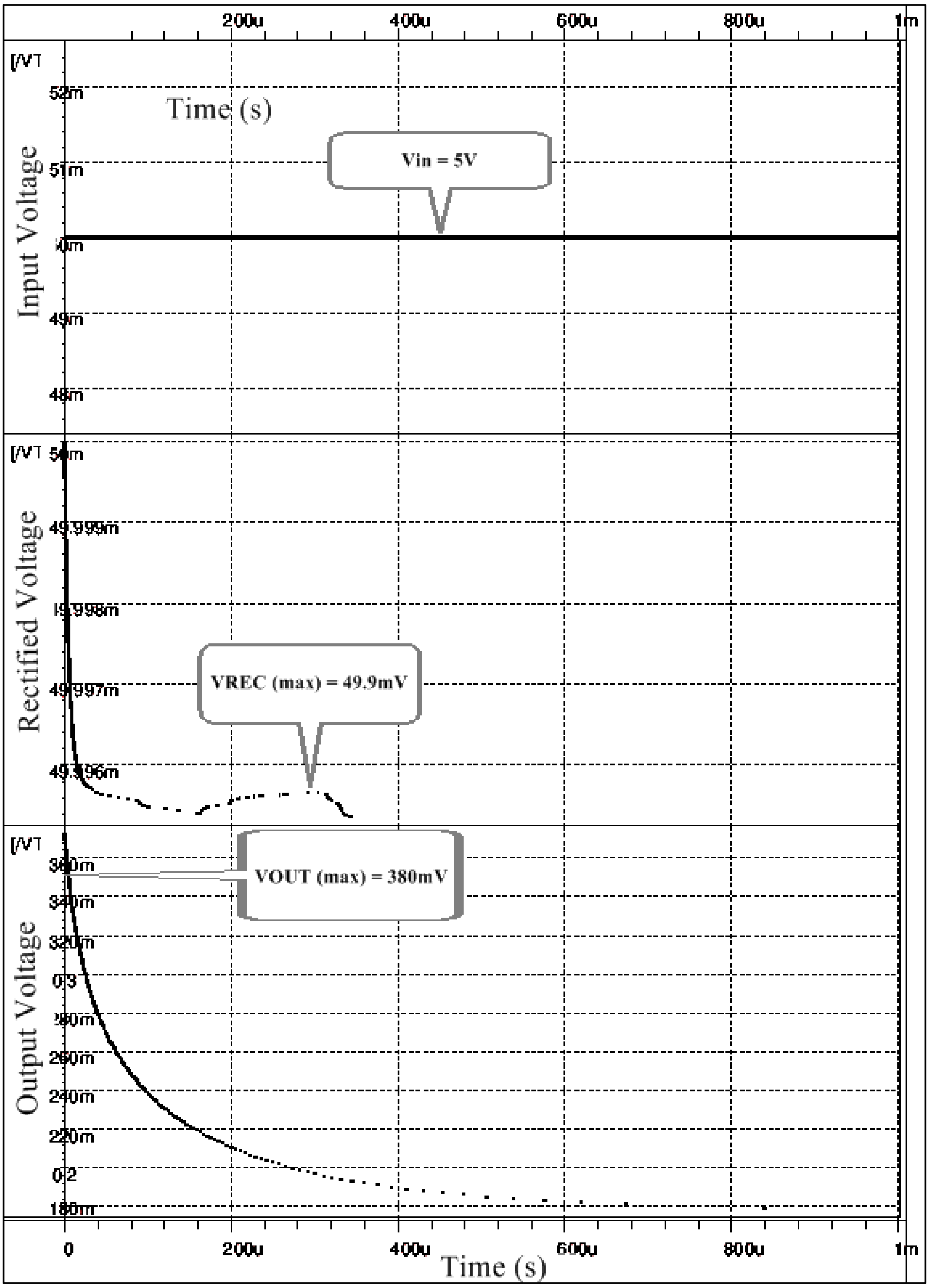
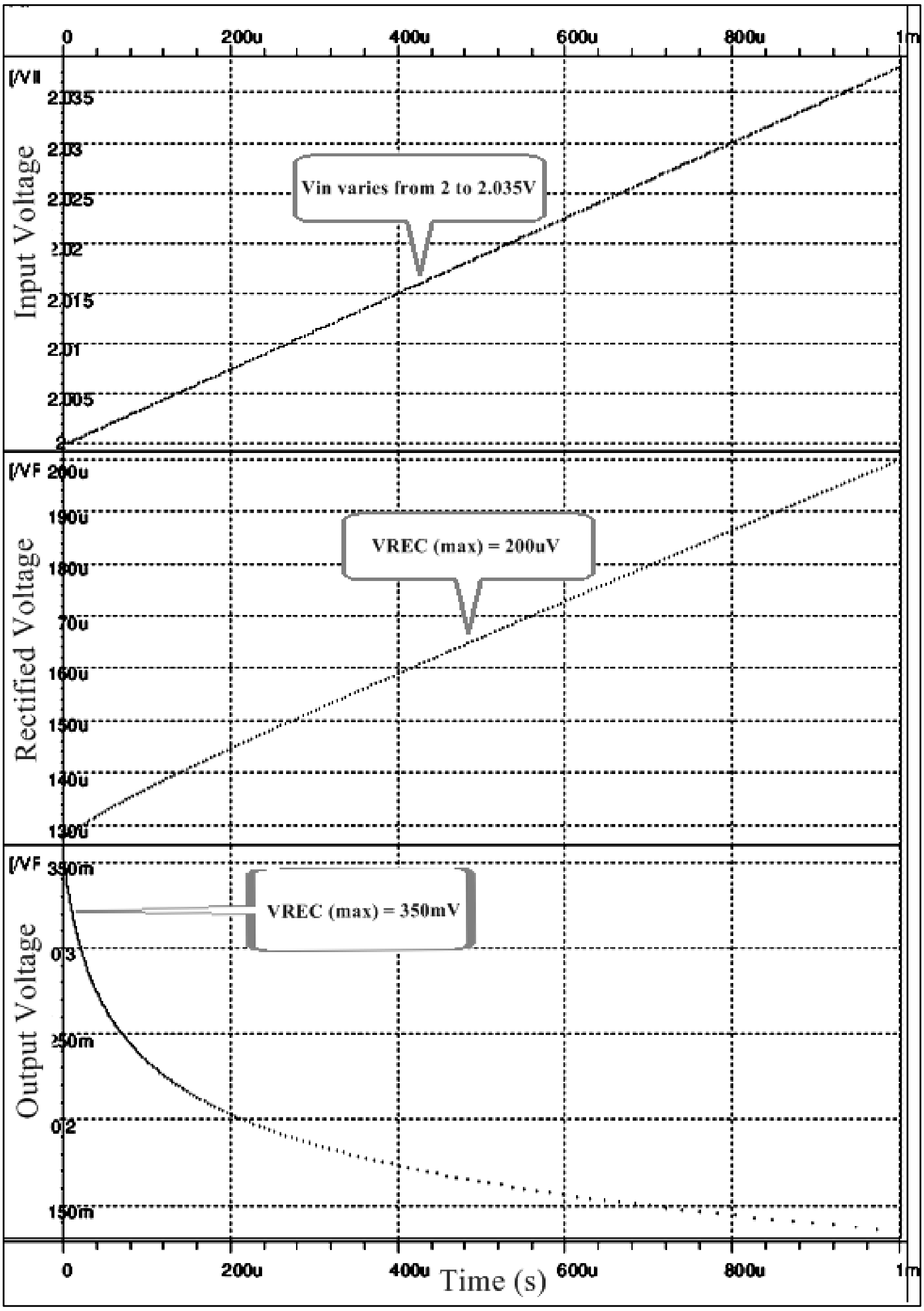
APPENDICES

APPENDIX A: Simulation Waveform for Thermal Energy Harvester



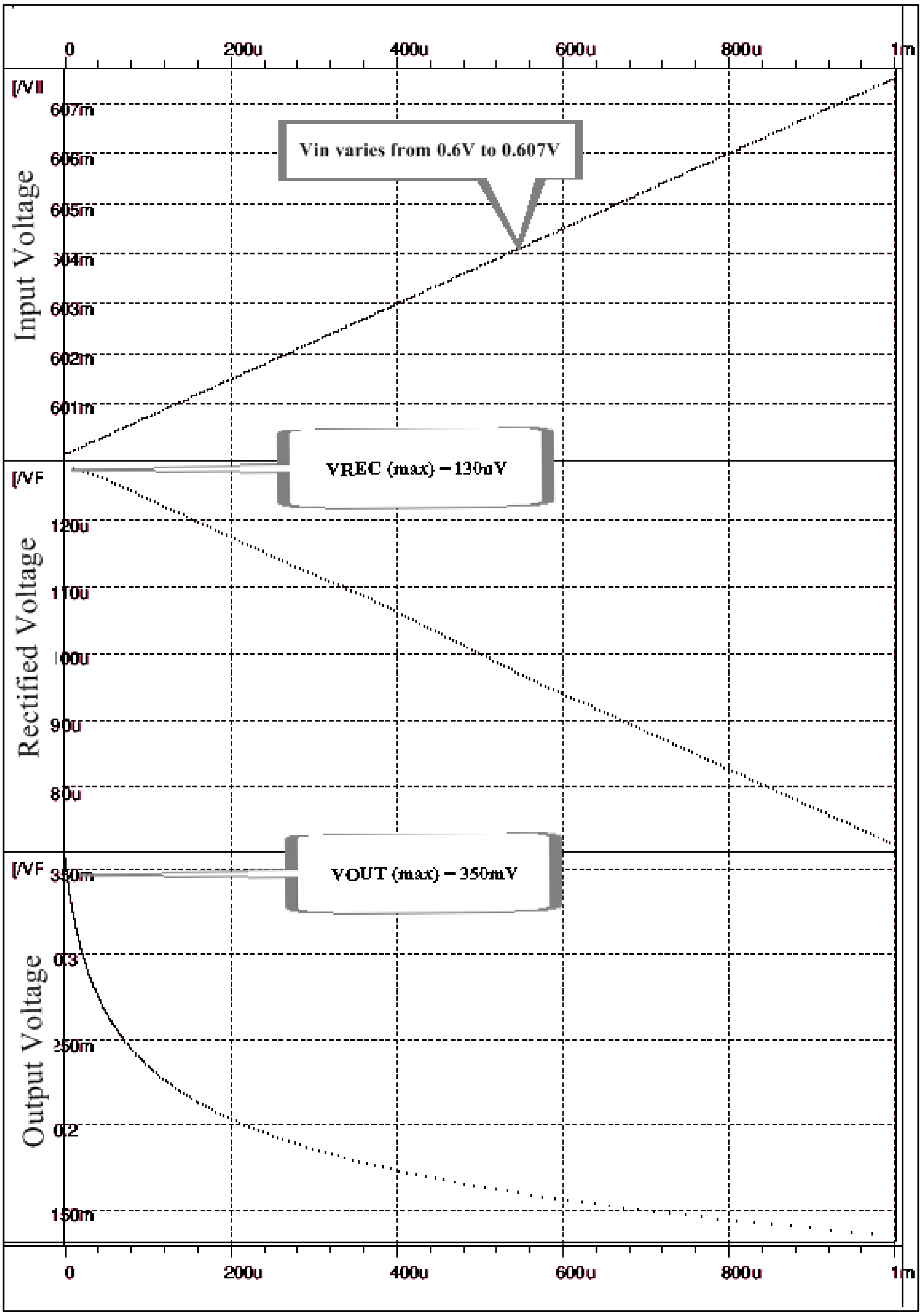
Graph A: Simulation Waveform for Thermal Energy Harvester

APPENDIX B: Simulation Waveform for RF Energy Harvester



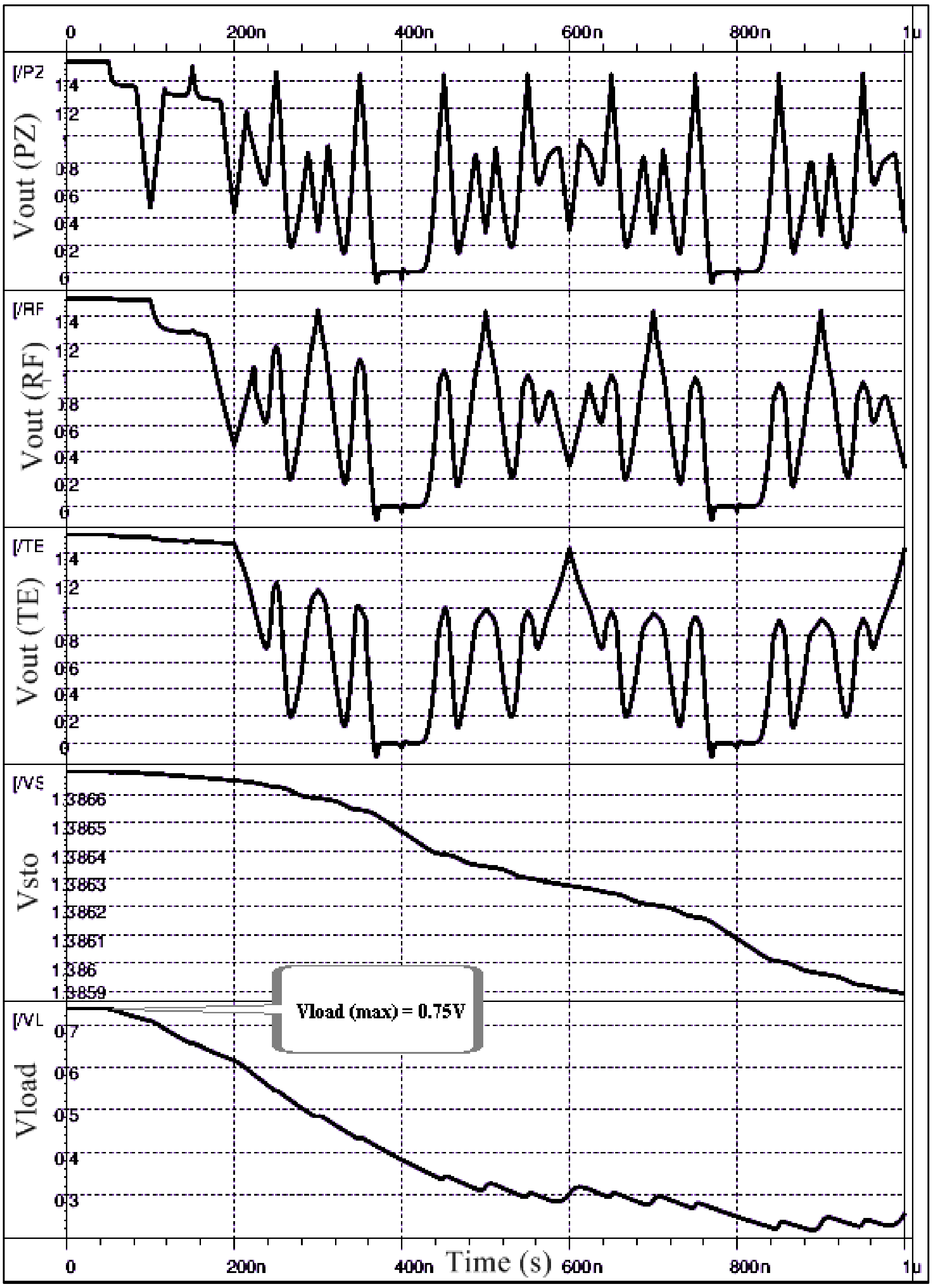
Graph B: Simulation Waveform for RF Energy Harvester

APPENDIX C: Simulation Result for Piezo Energy Harvester



Graph C: Simulation Result for Piezo Energy Harvester

APPENDIX D: Simulation Result for Multi-Source Harvester



Graph D: Simulation Result for Multi-Source Harvester