

**DESIGN OF RECTIFYING CIRCUIT WITH IMPROVED RF-DC  
CONVERSION FOR WIRELESS POWER TRANSFER**

**CHAN CHUN YEW**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**DESIGN OF RECTIFYING CIRCUIT WITH IMPROVED RF-DC  
CONVERSION FOR RF WIRELESS POWER TRANSFER**

**CHAN CHUN YEW**

**This Report Is Submitted In Partial Fulfillment of Requirements For The  
Bachelor Degree in Electronic Engineering (Telecommunication Electronics)  
With Honours**

**Faculty of Electronic and Computer Engineering**

**Universiti Teknikal Malaysia Melaka**

**June 2015**

**BORANG PENGESAHAN STATUS LAPORAN**

**PROJEK SARJANA MUDA II**

**Tajuk Projek** : Design of Rectifying Circuit with Improved RF-DC Conversion for Wireless Power Transfer

**Sesi Pengajian** : 

1	4	/	1	5
---	---	---	---	---

Saya .....CHAN CHUN YEW.....  
mengaku membenarkan Laporan Projek Sarjana Muda ini disimpan di Perpustakaan dengan syarat-syarat kegunaan seperti berikut:

1. Laporan adalah hakmilik Universiti Teknikal Malaysia Melaka.
2. Perpustakaan dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan laporan ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. Sila tandakan (  ) :

**SULIT\***

\*(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

**TERHAD\*\***

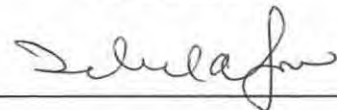
\*\* (Mengandungi maklumat terhad yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

**TIDAK TERHAD**

Disahkan oleh:



(TANDATANGAN PENULIS)



(COP DAN TANDATANGAN PENYELIA)


**DR. ZAHRILADHA BIN ZAKARIA**  
Profesor Madya  
Fakulti Kejuruteraan Elektronik Dan Kejuruteraan Komputer  
Universiti Teknikal Malaysia Melaka (UTeM)  
Hang Tuah Jaya  
76100 Durian Tunggal, Melaka

Tarikh: .....11/6/2015.....

Tarikh: .....11/6/2015.....

## DECLARATION

I declared that this thesis entitled “Design of Rectifying Circuit with Improved RF-DC Conversion for Wireless Power Transfer” is the result of my own research except as cited in the reference

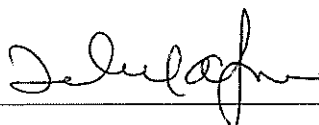
Signature :  \_\_\_\_\_

Name : CHAN CHUN YEW

Date : 11/6/2015

## APPROVAL

I hereby declared that I have read this thesis and in my opinion, this thesis is sufficient in term of scope and quality for the award of the Bachelor Degree in Electronic Engineering (Telecommunication Electronics) with Honours.

Signature :  \_\_\_\_\_

Name : PROF MADYA DR ZAHRIADHA BIN ZAKARIA

Date : 11/6/2015

## ACKNOWLEDGEMENTS

First of all, I would like to express my deepest appreciation to my supervisors, Prof Madya Dr Zahriladha bin Zakaria and Prof Madya Dr Abdul Rani bin Othman. Thanks to my supervisor PM Dr Zahriladha who will give suggestion, guidance and encouragement. With the guidance and suggestion, a lot of new input can be obtained and learned from that.

I also would like to extend my appreciation to my family and friends. Thanks to my parents for their support, financial support and encouragement. Besides, I also would like to appreciate my friends that assist me. Thanks to Lee Kah Weng who assists me solder the tiny SMD components. Thanks to Tan Kien Leong, who borrow his full sets of tool box for me to complete this project. Thanks to Sam Weng Yik that assist me on the project.

Last but not least, I would like to extend my appreciation to laboratory technician of FKEKK, Mr Mohd Sufianbin Abu Talib and Mr Imran bin Mohamed Ali, who helps to carry out the measurement process and teach the right way of the fabrication process. I also would like to appreciate the guidance and suggestion from panels of seminar who give comment and advice which can help me improve my project.

## ABSTRACT

Energy harvesting system is a system that able to generate power from the ambient sources such as Radio Frequency (RF), solar, wind, motional, thermoelectric, and piezoelectric. As the demand for power increased, energy harvesting system is found to be one of the methods that can be applied. Thus, a rectifying circuit for RF energy harvesting system was introduced. A single stage and double stage rectifying circuit are designed, simulated, fabricated and measured in this study by using the Agilent Advanced Design System (ADS) 2011. Simulation and measurement were carried out for various input power levels at frequency 2.45 GHz. An experimental study had been carried out by varying the load of the rectifying circuit, R. Voltage regulator circuit LP2951 is connected to the rectifying circuit in order to produce a stable regulated output voltage. An input power of 15dBm, the system managed to produce 3.838V for single stage rectifying circuit and 7.812V for the double stage rectifying circuit. When rectifying circuit connected with a voltage regulator circuit, whole system is able to produce 4.038V regulated output voltage at 20dBm for single stage and 4.07V regulated output voltage at 20dBm for double stage. From the measured output voltage result, the maximum efficiency is 8% for single stage rectifying circuit and 33% for the double stage rectifying circuit. The design of rectifying circuit can be used to run low power device such as emergence relief and temperature sensor. The rectifying circuit also can be used to charge up mobile phone.

## ABSTRAK

Sistem penuaian tenaga adalah satu sistem yang mampu menjana kuasa daripada sumber-sumber persekitaran seperti Frekuensi Radio (RF), solar, angin, penggerakkan, termoelektrik dan piezoelektrik. Disebabkan permintaan terhadap kuasa meningkat, sistem penuaian tenaga didapati merupakan salah satu kaedah yang boleh digunakan. Oleh itu, reka bentuk litar untuk RF sistem penuaian tenaga diperkenalkan. Satu and dua peringkat litar direka bentuk, simulasi, fabrikasi dan diukur dalam kajian ini dengan menggunakan perisian Advance Design System (ADS) 2011. Simulasi dan pengukuran telah dijalankan bagi pelbagai tahap kuasa input pada frekuensi 2.45 GHz. Satu uji kaji telah dijalankan dengan mengubah beban litar, R. Litar Voltan pengatur LP2951 turut disambungkan dengan litar untuk menghasilkan voltan keluaran terkawal yang stabil. Bagi kuasa masukan sebanyak 15dBm, sistem berjaya menghasilkan 3.838V bagi litar satu peringkat dan 7.812V untuk litar peringkat berganda. Apabila litar disambungkan dengan litar pengatur voltan, seluruh system mampu menghasilkan voltan keluaran yang terkawal selia pada 20dBm adalah sebanyak 4.038V untuk peringkat satu dan voltan keluaran yang terkawal selia pada 20dBm adalah sebanyak 4.07V untuk peringkat berganda. Dari hasil voltan keluaran diukur, kecekapan maksimum ialah 8% bagi litar peringkat satu dan 33% untuk litar peringkat berganda. Litar boleh digunakan untuk menjalankan peranti kuasa rendah seperti isyarat kecemasan dan pengesahan suhu. Litar juga boleh digunakan untuk mengecas telefon mudah alih.



## TABLE OF CONTENTS

CHAPTER	TITLE	PAGES
	<b>PROJECT TITLE</b>	<b>ii</b>
	<b>APPROVAL</b>	<b>iii</b>
	<b>ACKNOWLEDGEMENT</b>	<b>iv</b>
	<b>ABSTRACT</b>	<b>v</b>
	<b>ABSTRAK</b>	<b>vi</b>
	<b>TABLE OF CONTENTS</b>	<b>vii</b>
	<b>LIST OF TABLES</b>	<b>xi</b>
	<b>LIST OF FIGURES</b>	<b>xiii</b>
	<b>LIST OF ABBREVIATIONS AND ACRONYMS</b>	<b>xvii</b>
	<b>LIST OF APPENDIXES</b>	<b>xviii</b>
<b>I</b>	<b>INTRODUCTION</b>	
	1.1 RESEARCH BACKGROUND	1
	1.2 PROBLEM STATEMENT	3
	1.3 OBJECTIVES	3
	1.4 SCOPE OF PROJECT	4
	1.5 METHODOLOGY	
	1.5.1 PROJECT PLANNING	5
	1.5.2 DATA COLLECTION	5
	1.6 CONTRIBUTION	6
	1.7 ORGANIZATION OF THESIS	7

## II LITERATURE REVIEW

2.1	INTRODUCTION	8
2.2	RECTIFYING CIRCUIT	11
2.3	VOLTAGE MULTIPLIER	13
2.4	NUMBER OF STAGE	14
2.5	MATCHING NETWORK	17
2.6	DIODE FOR RECTIFYING CIRCUIT	18
2.7	LOADS FOR RECTIFYING CIRCUIT	19

## III RESEARCH METHODOLOGY

3.1	INTRODUCTION	20
3.2	RECTIFYING CIRCUIT	22
3.2.1	LUMPED ELEMENTS DESIGN	23
3.2.2	MICROSTRIP DESIGN	24
3.2.3	LAYOUT DESIGN	27
3.3	TUNING FOR OPTIMIZATION	28
3.4	FABRICATION AND MEASUREMENT	30
3.5	VOLTAGE REGULATOR	30
3.5.1	LP2951-N SERIES OF ADJUSTABLE MICROPOWER VOLTAGE REGULATOR	32
3.5.2	LTC3588-2 NANOPOWER ENERGY HARVESTING POWER SUPPLY WITH 14V MINIMUM $V_{IN}$	35
3.5.3	LMR61428 SINGLE SWITCHER 14 $V_{OUT}$ , 2.85A STEP UP VOLTAGE REGULATOR IN VSSOP	36

<b>IV</b>	<b>RESULTS AND DISCUSSION</b>	
4.1	INTRODUCTION	38
4.2	SIMULATION RESULT	38
4.2.1	SCHOTTKY DIODE	38
4.2.2	STAGES OF THE RECTIFYING CIRCUIT	40
4.2.3	LOAD OF THE RECTIFYING CIRCUIT	43
4.3	VOLTAGE REGULATOR	51
4.3.1	LP2951-N SERIES OF ADJUSTABLE MICROPOWER VOLTAGE REGULATOR	51
4.3.2	LTC3588-2 NANOPOWER ENERGY HARVESTING POWER SUPPLY WITH 14V MINIMUM $V_{IN}$	53
4.3.3	LMR61428 SINGLE SWITCHER 14 $V_{OUT}$ , 2.85A STEP UP VOLTAGE REGULATOR IN VSSOP	55
4.4	EXPERIMENTAL RESULT	59
<b>V</b>	<b>CONCLUSION AND FUTURE WORKS</b>	
5.1	CONCLUSION	68
5.2	SUGGESTION FOR FUTURE WORKS	69
	<b>REFERENCES</b>	70
	<b>APPENDIXES</b>	74

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGES</b>
2.1	Summary of the literature review	10
3.1	Interdigital Capacitor Parameters	25
4.1	Output voltage of single-stages rectifying circuit with different load and input signal	44
4.2	Output current of single-stages rectifying circuit with different load and input signal	45
4.3	Output voltage of double-stages rectifying circuit with different load and input signal	45
4.4	Output current of double-stages rectifying circuit with different load and input signal	46
4.5	Output Power of single-stages rectifying circuit with different load and input signal	47
4.6	Output Power of double-stages rectifying circuit with different load and input signal	48
4.7	Efficiency of single-stages rectifying circuit with different load and input signal	49
4.8	Efficiency of double-stages rectifying circuit with different load and input signal	49
4.9	Regulated output when input voltage dropped from 14V	52
4.10	Regulated output voltage when input voltage increases	54

4.11	Regulated output voltage when input voltage increased	57
4.12	Regulated output voltage when input voltage dropped from 5V	58
4.13	Output voltage of single stage rectifying circuit	61
4.14	Regulated output voltage of single stage rectifying circuit with connected to voltage regulator circuit	62
4.15	Output voltage of double stage rectifying circuit	63
4.16	Regulated output voltage of double stage rectifying circuit with connected to voltage regulator circuit	65
4.17	Comparison of simulation output voltage of single stage rectifying circuit with measured output voltage of single stage rectifying	66
4.18	Comparison of simulation output voltage of double stage rectifying circuit with measured output voltage of double stage rectifying	67

## LIST OF FIGURES

<b>FIGURE</b>	<b>TITLE</b>	<b>PAGES</b>
1.1	Block diagram of RF energy harvesting	2
1.2	Gantt chart of the project	5
2.1	Basic single rectifying circuit	12
2.2	Villard voltage doubler	13
2.3	Dickson voltage doubler	14
2.4	Cockcroft walton voltage doubler	14
2.5	Effect of number of stages on maximum voltage gain	15
2.6	Effect of number of stages on output DC voltage	16
2.7	Effect of number of stages on input impedance of rectifier	16
2.8	Schematics of (a) single-stub impedance transformers shunt-series configuration and (b) single-stub impedance transformers series-shunt configuration	17
2.9	Output voltage varies with each type of diode	18
2.10	Effect of load impedance on the efficiency of the rectifying circuit	19
3.1	Flow Chart of the project	21
3.2	Schematic of the lumped elements design for the single stage rectifying circuit	23
3.3	Interdigital Capacitor	24

3.4	Interdigital capacitor MiCapS in passive circuit DG-RLC of ADS 2011	26
3.5	Interdigital capacitor schematic in ADS 2011	26
3.6	Microstrip line design	27
3.7	LineCalc tool	27
3.8	Momentum layout design	28
3.9	Substrate layout in momentum	28
3.10	Parameters selected in tuning tool	29
3.11	Result of rectifying circuit before tuning (blue) and after tuning (red)	29
3.12	Measurement setup for rectifier and voltage regulator	31
3.13	Adjustable output voltage of voltage regulator LP2951-N circuit	33
3.14	Input voltage vs output voltage of LP2951-N	34
3.15	Schematic of LP-2951-N in OrCAD	34
3.16	High voltage piezoelectric energy harvesting power supply	35
3.17	LTC3588-2 5.0V regulator start-up profile	36
3.18	Typical application of LMR61428	37
3.19	Schematic of LMR61428 in OrCAD	37
4.1	Diode characteristic of each type of diodes	38
4.2	Single stage rectifying circuit	40
4.3	Output voltage of single stage rectifying circuit	41
4.4	Double stage rectifying circuit	42
4.5	Output voltage of double stage rectifying circuit	43
4.6	Comparison of single stage output voltage of different load resistance	46
4.7	Comparison of double stage output voltage of different load resistance	47
4.8	Efficiency of single-stages rectifying circuit vs different input signal with different load resistances	50

4.9	Efficiency of double-stages rectifying circuit vs different input signal with different load resistances	50
4.10	Simulation result of LP2951-N with input from 0V to 14V	51
4.11	Simulation result of LP2951-N with input from 14V to 12V	52
4.12	Regulated Output Voltage vs Input Voltage (Dropped)	53
4.13	Regulated output voltage for 14V input voltage	54
4.14	Regulated output voltage vs input voltage.	55
4.15	Simulation result of LP2951-N with input from 0V to 14V	56
4.16	Simulation result of LP2951-N with input from 0V to 3.5V	56
4.17	Simulation result of LP2951-N with input from 5V to 3.5V	57
4.18	Regulated output voltage vs input voltage	58
4.19	Regulated output voltage vs input voltage (dropped)	59
4.20	Double stage rectifying circuit prototype	60
4.21	Voltage regulator circuit prototype	60
4.22	Rectifying circuit connected with voltage regulator measurement setup and measurement take using vector signal generator	61
4.23	Output voltage vs input power of single stage rectifying circuit	62
4.24	Regulated output voltage vs input power of single stage rectifying circuit with connected to voltage regulator circuit	63
4.25	Output voltage vs input power of double stage rectifying circuit	64
4.26	Regulated output voltage vs input power of double stage rectifying circuit with connected to voltage regulator circuit	65



4.27	Comparison of simulation and measured of output voltage of single stage rectifying circuit vs input power of single stage rectifying circuit	66
4.28	Comparison of simulation and measured of output voltage of double stage rectifying circuit vs input power of double stage rectifying circuit	67

**LIST OF ABBREVIATIONS AND ACRONYMS**

RF	Radio Frequency
ADS	Agilent Design System
DC	Direct Current
AC	Alternating Current
PCB	Printed Circuit Board

**LIST OF APPENDIXES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Data Sheet of Schottky Diode HSMS 286B	
B	Data Sheet of LP295x-N Series of Adjustable Micropower Voltage Regulators	
C	Data Sheet of LTC3588-2 Nanopower Energy Harvesting Power Supply with 14V Minimum $V_{IN}$	
D	Data Sheet of LMR61428 SIMPLE SWITCHER® 14Vout, 2.85A Step-Up Voltage Regulator in VSSOP	
E	Innotek	
F	Fabrication Process	

## **CHAPTER I**

### **INTRODUCTION**

#### 1.1 Research Background

In recent years, the demand on the energy harvesting circuit for power and energy harvesting application has been increased. There are several types of energy harvesting, such as Radio Frequency (RF) energy harvesting, solar energy harvesting, wind energy harvesting, emotional energy harvesting, thermo-electric energy harvesting, and piezoelectric energy harvesting that can used to capture the energy from a controlled or ambient environment to power on the devices directly or store the energy in capacitors or in batteries. Energy harvesting is widely used for the low power device and low power circuit such as sensor, biomedical implants and radio frequency identification (RFID) [1].

Figure 1.1 shows the block diagram of the energy harvesting system. The source of the radio frequency (RF) can be generated from base stations, wireless internet, satellite communication, radio, TV and etc. The general energy harvesting system consists of an antenna that harvest RF energy, a matching circuit that connected between antenna and rectifier and power storage or port that can connect to a device. The basic functionality of the RF energy system is the antenna will receive the RF signal, then it will pass to rectifying circuit to perform conversion from RF to DC by diode. Then converted DC energy will be stored in storage device or directly as a power source to a low power consumption device.

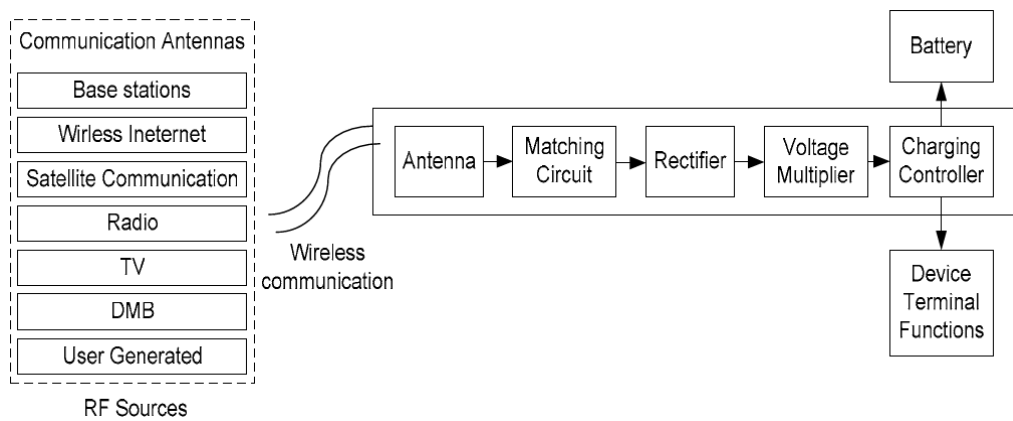


Figure 1.1: Block diagram of RF energy harvesting, courtesy of [2]

Furthermore, RF energy harvesting also can overcome the limited use of Wireless Sensor Networks (WSNs) that conventionally rely on battery. Application of RF energy harvesting in WSNs is able to reduce the cost of maintenance and extend the operation period of the WSNs [3].

## 1.2 Problem statement

Finite electrical battery life provides researchers and company's motivation to generate a new idea and technologies produce wireless mobile devices to have an infinite or enhanced period of time [2]. Battery in wireless mobile devices is the main power source of power on the device. Batteries in wireless mobile devices increase the size of the device. Besides, the battery is not environmentally friendly and cause pollution the environment [4]. RF energy harvesting is able to support various applications. Besides, RF energy harvesting can increase the lifetime of the devices. RF energy harvesting is able to reduce or eliminate the usage of the battery in the devices [1]. The challenge of this technology is the efficiency of the RF energy harvesting system to convert the RF energy into DC energy. Due to the rectifying circuit mostly will affect the performances of the energy harvesting system. Thus, the design of the rectifying circuit has to provide a great efficient in converting RF energy to DC. The ON/OFF characteristic and the threshold voltage of the diode in the rectifying circuit will affect the RF-DC conversion performance of the rectifying circuit [5]. In recent design such as [1] use CMOS to design the rectifier circuit. This type of method increases the cost to produce the rectifying circuit and cannot produce high DC voltage. Thus, by using a Schottky diode that provides low forward voltage and high switching speed and increase the stages of the rectifying circuit can increase the efficiency of RF-DC conversion for the rectifying circuit.

## 1.3 Objectives

The objectives of this project are to develop a high efficiency and low consumption of RF-DC conversion for rectifying circuit to covert the Radio Frequency (RF) energy into direct current (DC). In order to achieve this, some of the objectives need to be accomplished:

- a. To design a rectifying circuit in order to improve the RF-DC conversion
- b. To analyze the performance of rectifying circuit.
- c. To fabricate and validate the simulation results with experimental results in the laboratory.

#### 1.4 Scope of Project

The main objective of this project is to design a rectifying circuit with high efficiency and low consumption of RF-DC conversion for RF wireless power transfer. Before the design the rectifying circuit, firstly we have to do research on the RF energy harvesting to narrow down the scope of the research which is on rectifying circuit. Research can be based on journals from the internet or library. The focus of this project is to design, analyze, fabricate, test and measure the rectifying circuit to improve the RF-DC conversion for RF wireless power transfer. The software will be used to develop and analyze for the rectifying circuit is Agilent Advance Design System (ADS2011). Firstly, the analysis will be working on Schottky diode in the rectifying circuit. The Schottky diode must have a low forward voltage and high output voltage. Next, the analysis will be work on the stages of the rectifying circuit. Analysis only will work on the single stage and double stages of the rectifying circuit. Stages of the rectifying circuit can affect the performance of the rectifying circuit. Then, analysis will be carried on varies the value of the load resistor in the rectifying circuit from a range of  $100 \Omega$  to  $1 \text{ M}\Omega$ . Then, design a voltage regulator to maintain the DC level from the rectifying circuit. Next, design a simple matching circuit and carry out the analysis of the matching circuit. When the rectifying circuit with impedance matching completed, the fabrication of rectifying circuit can carry out. Then, testing and measuring will carry out on the rectifying circuit. Finally, the rectifying circuit will be combined with antenna in order to carry out testing for the whole RF wireless power transfer system by using the lab equipment to measure the performance of the RF-DC conversion of the rectifying circuit.

## 1.5 Methodology

### 1.5.1 Project Planning

Project Planning is very helpful in tracking the progress of the project. A Gantt chart is constructed to implement the project. The Gantt chart is prepared for the purpose of to ensure the all the progress are meets the dateline and achieves the milestones. Figure 1.2 shows the Gantt chart of the project and milestone of the project.

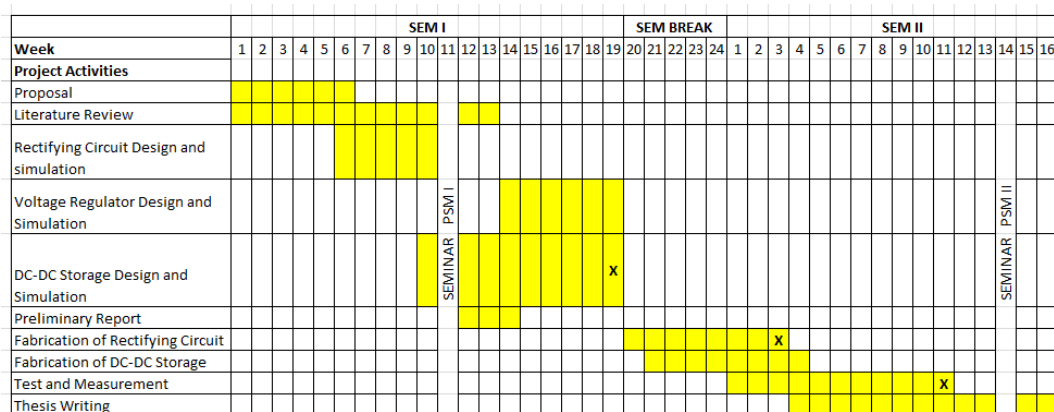


Figure 1.2: Gantt chart of the project.

### 1.5.2 Data Collection

Literature review is the first step has to be done before start to design the rectifying circuit. The literature review will be the focus of the research paper or journal that related to the RF energy harvesting and rectifying circuit. Literature