DESIGN OF AN EFFICIENT RECTIFIER CIRCUIT FOR RF ENERGY HARVESTING



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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TECHNOLOGY

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DECLARATION

I hereby, declared this report entitled DESIGN OF AN EFFICIENT RECTIFIER CIRCUIT FOR RF ENERGY HARVESTING is the results of my own research except as cited in references.



APPROVAL

This report is submitted to the Faculty of Electrical and Electronic Engineering Technology of Universiti Teknikal Malaysia Melaka (UTeM) as a partial fulfilment of the requirements for the degree of Bachelor of Electronics Engineering Technology (Telecommunication) with Honours. The member of the supervisory is as follow:



ABSTRAK

Penyelidikan ini menerangkan reka bentuk litar penerus yang berkesan untuk frekuensi radio penuai tenaga. Frekuensi radio penuain tenaga adalah proses untuk menghasilkan dan menuai tenaga dari sumber luaran. Ini adalah teknologi hijau yang dapat diakses secara meluas di ruang angkasa. Lengkapkan sumber tenaga rendah yang digunakan untuk menghidupkan peranti elektronik berkuasa rendah. Litar penerus Bridge dicadangkan untuk menukar Frekuensi radio ke Arus terus. Frekuensi tetap 2GHz dicadangkan untuk pengukuran dan simulasi tahap daya input yang berbeza. Terdiri daripada rangkaian penerus yang berpotensi LC dan diod Schottky. Proses simulasi litar ADS 2017 digunakan untuk reka bentuk sistem ini.

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ABSTRACT

This research describes the design of an effective rectifier circuit for RF Energy Harvest. RF Energy Harvest is a process for producing and harvesting energy from an external source. This is a green technology that is widely accessible in space. Complement the low-energy sources used to power low-power electronics devices. A Bridge rectifier circuit is proposed to convert RF to DC. Fixed frequency 2Ghz is proposed for the measurement and simulation of different input power levels. Consists of a combination of LC impedance matching network and Schottky diodes. The ADS 2017 circuit simulator is used for this design of the system.

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DEDICATION

Alhamdulillah, praise to the Almighty Allah

S.W.T This thesis is dedicated to:

My beloved family,

My Parents,



ACKNOWLEGDMENT

In the name of Allah S.W.T, the most gracious and merciful. I want to thank my project supervisor and co-supervisor for the support they have given me to finish my final year project. I would like to thank my project supervisor and co-supervisor for the help they have given me to finish my final year project. Knowledge and suggestion supported me in such a huge way. Next, I would like to say thank you to my family especially my parents because they were always there to give me support emotionally and financially whenever I needed it especially in my hard times. I would like to thank to all of my family members who always give me the support in encouragement and have faith in me in completing my studies at Universiti Teknikal Malaysia Melaka (UTeM). Lastly, special thanks to all my friends who have kindly helped me in advices and such more in order to complete this project. May Allah repay all of your kindness, thank you.

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CHAPTER 1

INTRODUCTION

1.1 Background

Ambient power or also commonly known as Energy scavenging is a mechanism whereby energy is obtained and extracted from an external source. Energy harvesting has been shown to be extensively used for small and mobile system device such as wearable electronics. There are humongous sources of energy production such as wind energy, solar energy and kinetic energy. According to (Rengalakshmi and Brinda, 2016)(Re Energy scavenging is originally based on the wind-driven wheel and also waterwheel.

The collection of power from propagating radio frequency (RF) signals is one of the most common power extraction method of passive controlled devices. The process of converting energy from electromagnetic (EM) into electrical domain described as the RF energy scavenging. Energy harvesting is divided into two small and large scale categories. RF energy is on small scale categories (Rengalakshmi and Brinda, 2016). Examples of radio signals generated in our daily lives are TV signals, wireless network and cell tower. Throughout the field of communication, the RF signal is widely used (ElAnzeery and Guindi, 2012).

In future microelectronic circuits, RF Energy Harvesting has an important role to play (Din, 2012). The power source transmits in a very wide (kW) range. However, the receiver receives only a small-scale of range. The energy residue as heat is dissipated. Then, the unused energy could be transformed to produce small amount of electricity. RF-powered devices are usually used in employments such as structural control, considering difficulty to replace the battery without harming structure as in Figure 1.1.



Figure 1. 1: Communication links between the base station (hub) and sensors in passively sensor network(Binti Amilhajan, 2014).

1.2 Problem Statement

Wireless power transmission (WPT) established almost a century ago and began to evolve day by day. Smartphone and IoT technology is an example of the use of wireless application. Many developers and researcher have begun using harvesting ambient RF energy to eliminate battery-based system. The reason for removing the battery-based system is because due to the operating life time and to continuously changing the battery. Moreover, the deposition of the battery creates environmental emissions. There is also an increasing demand for the use of ambient RF energy technology as it allows wireless charging of low-power devices and has resulting benefits for product design, usability and reliability.

In addition, there are many challenges to the design of a circuit for RF energy harvesting, in particular for energy conversion efficiency. Several researchers have performed studies on the nature of the RF energy system. RF energy harvesting is split into two parts for low-power and wide input power ranges. There a few scenarios the need to considered such the amount of RF energy that have not been used and number of the RF tower around that area that may produce the outcomes. To produce a good DC-conversion voltage and optimum efficiency, the rectifier circuit need to be designed by using lump elements and active element such as Schottky diode.

1.3 Objective

- I. To design the rectifier circuit with impedance matching network.
- II. To implement the rectifier circuit with impedance matching network.
- III. To verify the measurements value towards simulation results.

1.4 Scope of work

Scopes are recorded to ensure the project will be inside its expected point of confinement. The scope will be functional to ensure those project is going in the correct course with the achieve the goal. In the process of the designing Energy Harvesting system, the main objective of this project is rectifier circuit. It consists of diode and capacitor. The basic concept of an Energy Harvesting is shown in Figure 1.2 and it consists of antenna that receive/transmit signals within a certain frequency range connected to a rectifier (AC/DC converter) (Keyrouz, Visser and Tijhuis, 2012).



Figure 1.1: Energy Harvesting System(Keyrouz, Visser and Tijhuis, 2012).

Agilent Advanced Design System (ADS) 2017 will be used for design process of rectifier circuit. Bridge rectifier with fixed frequency 2GHz is proposed. It consists of four diodes. The schottky diodes are used because it suitable for the weak RF signal environment, low recovery time and provides high efficiency for RF-to-DC. Next, it will follow by variations of load where the load varying from 50 Ω to 100 k Ω . Then, the lump elements will be including to improves the conversion efficiency of the circuit. After testing and simulation, the rectifier circuits will be manufactured.



CHAPTER 2

LITERATURE REVIEW

2.1 Rectifiers with Low Input Power Applications

Recently, there's a growing interest within the design of low-power circuits by using microstrip antenna (Kundu (Datta) et al., 2017). It allows Energy Harvesting (EH) systems to be ready to feed electronics circuits that execute complex process and play a crucial role in several application areas. Consistent with (Din, 2012) there are two reasons why this work is administered by a number of researchers who are freely available in space and complement the low-energy sources used to power low-power electronic devices, Green Technology. It consists of antenna that collect electromagnetic energy which convert the collected RF energy to dc power, so on replace the necessity for batteries.

The author in (Rengalakshmi and Brinda, 2016) designed an energy harvesting system which scavenges energy from RF electromagnetic spectrum and its operated in GSM 900 band. Based on the lab test the rectifier efficiency are around 72% for low input power. In (Din, 2012) the system is focused to supply source of energy for energizing low power devices. The E-shaped antenna was proposed from the traditional wide band microstrip antennas and including another subsystem which is a π impedance combination and 7-stage voltage doubler circuit. The design and simulation were performed using Multisim software. Based on the field test the DC voltage acquired was 2.9V and was enough to power the STLM20 temperature sensor. In (Razavi Haeri *et al.*, 2017) proposed rectifier circuit for ambient energy that priority in Ultra-low power

applications. This was achieved by designing 50-stage Dickson rectifier and manufactured using a 180 nm TSMC CMOS layout. The input voltage for IC is 900 MHz that standardizes for true comparison value. Thus, a 50-ohm input impedance network was set up at the input of the IC. However, an identical network will be used to supply a passive system in the actual configuration of the harvester.

Typically, rectennas cannot be directly compare, as they function in different amounts of control, and different concepts of efficiency can be used in different articles more objectively. Table 2.1 lists the performance satisfactory RF to DC conversion at low input power densities. However, GSM 900 is on the top of public telecommunications band for the RF energy harvesting densities.

Reference	Frequency(GHZ)	RF-to-DC(%)			
(Kasar, Gözel and	1	Single-stage	70.5		
Kahriman, 2019)	TI TEKNIKAL MA	LAYSIA MELAKA			
(Razavi Haeri et al.,	0.9	50-Stage voltage	60		
2017)		double rectifier			
(Kundu (Datta),	2.5	Bridger	50		
Acharjee and					
Mandal, 2017)					
(Rengalakshmi and	0.945	Voltage double	72		
Brinda, 2016)		rectifier			
(Song <i>et al.</i> , 2015)	1.8-2.5	Full-wave Grienacher	55		
(Chuc and Duong,	2.45	Voltage Doubler	70.06		
2015)					
(Tudose and	2.45	Voltage Doubler	67		
Voinescu, 2013)					
(ElAnzeery and	0.5-9	N-stage Multiplier	NA		
Guindi, 2012)					

Table 2. 1: Comparison of Power conversion efficiency

(Din, 2012)	0.8	7-Stage voltage double rectifier	30-50		

2.2 Rectifiers with Wide Operating Input Power Ranges

As the development of wireless technologies grow instantly, the density of wireless surrounding increasing due to growing amount of electromagnetic sources. Definition of electromagnetic sources that are the Tx-Rx tower and WiFi-routers. In the past few years, the purpose of making use RF energy has obtained a great deal of demand in terms of saving service expenses and replacing the, also known a battery. Wireless power transmissions (WPT) employs aerial technology is considered a sensible result for converting ambient RF power to functional Dc voltage. Research in the field of rectenna leads to tonnes of development, which is broadly supported WPT and energy scavenging for the past decades (Song et al., 2015). In general, wireless charging implementations (Marian et al., 2012), are protected by three scenarios. As shown in figure 2.1, a solid emitter is where wireless energy is transmitted in close proximity to the sensor region. The RF power level is normally high because the distance is low. The next state is that the RF power can be transmitted from a fairly long distance through a high-power transmitting antenna. The RF power level is lower in this case due to a path failure. The third approach uses RF energy in the atmosphere and RF measure is very inadequate. Thus, it is ideal that a rectenna achieve a high Power conversion efficiency (PCE) from RF to DC over a broad scale input.



Figure 2. 1: Wireless charging situations. (a) Proximity of load. (b) Remote charging. (c) RF energy scavenging(Hucheng, 2014).

We are aware that the rectifier is in critical in WPT systems for the RF to DC transmission PCE. Various types of rectifiers have been developed for WPT applications (Divakaran, Krishna and Nasimuddin, 2019). The right diode selection depends on input power levels for a rectifier configuration. For low-supply systems a significant part of input supply is use in order to resolve the threshold voltage if input current is low. Diodes with low-input power voltage are favored. In addition, for peak supply applications the diodes with high breakdown voltage are suitable. Therefore, diodes with low threshold voltage and high breakdown voltage must be chosen in order to design a rectifier with wide range input power. Consequently, due to the inherent non-linearity of the diode, each of these conventional rectifiers can only perform a satisfactory RF to DC PCE with a narrow input power (Marian et al., 2012). A new topology is required to fulfill broad functioning wattage range, simplify the design process and reduce advanced manufacturing technology requirements.

In (Kasar, Gözel and Kahriman, 2019) study of single and N-stage of Dickson rectifier would be capable of carrying out RF energy scavenging were suggested. The Dickson rectifier circuit gives feedback to small amount of current and voltage, contributes in efficiency of Power conversion which produce high output voltage. Operating at 1GHz and the maximum PCE is 70.5%-77%. 1.8V Dc voltage is the peak of output voltage and 5.16V in 3 stage. Moreover, the efficiency of the rectifier circuit was determined by using equation (2.11). Where, P_{in} is the input power, P_{DC} is the value power collected at the output from load resistance.

$$PCE = \frac{P_{DC}}{P_{in}} \tag{2.1}$$

The efficiency analysis was performed according to different input powers according to one of the key output parameters of rectifiers circuits. In (Divakaran, Krishna and Nasimuddin, 2019) the main objective is to apply the operating power supply to the Internet of Things (IoT). Another interesting alternative in cases where solar harvests are not feasible is the RF energy harvesting. However, despite a well-developed RF communication system architecture, the RF energy harvesting systems are facing with several challenges especially for the harvesting of RF signals in the ambient environment. The overall conversion performance, width and form factor can be loosely defined as the challenges. The RF source is an alternative due to its continuous availability but it suffers from low incident power levels. However, dedicate source and effective DC conversion circuits can accommodate wide input operating ranges can be enhanced. Table 2 contrast energy transmission in the near and far fields. The near field transmission is used to power home appliances, while far field transmission still poses a number of research challenges, particularly in improving its conversion efficiency.

Table 2. 2: RF power transmission characteristics (Divakaran, Krishna and

Characteristics	Far field transfer	Resonant coupling	inductive coupling			
Field	EM	Resonance (Electric or EM)	Magnetic method			
Method	Antenna	Resonator	Coil			
Efficiency	Low to High	High	High			
Distance	Short to Long	Medium	Short			
Power	Low to High	High	High			
Safety	EM	None	Magnetic			
Regulation	Radio wave	Under discussion	Under discussion			

Nasimuddin, 2019).

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A new broadband rectenna for environmental wireless energy processing over

the frequency range from 1.8 to 2.5 GHz is proposed (Song et al., 2015). Studies of measurement area are the characteristic of ambient RF divided into three scenarios which are indoor, outdoor and semi-indoor. It may be uses to boost a lot of sensors even low-power electronic devices and discovered wide scale of prospects application. As measure the power sensitivity is dropped to -35dBm and the maximum changing proficiency climbs up to 55% when rectifier has the input power of -10dBm. In terms of incident power and bandwidth the architecture is very different from traditional rectenna models. A modern rectifier circuit to scale down the RF energy utilization improve the electricity efficiency. Furthermore, the broadband rectenna with different low input energy stages is

being complemented by a new impedance matching circuit. Therefore, an improved design is proposed, as shown in Figures 2.2 and 2.3, for a voltage double rectifier.



Figure 2. 2: Impedance network with voltage doubler rectifying circuit(Song et al.,



Figure 2. 3: Circuit diagram of full-wave Grinacher with a pair matching

network(Song et al., 2015).

2.3 Rectifiers Circuit Design

The main objective of the RF energy harvesting system is the Power Conversion Efficiency of RF to DC. The RF energy harvesting system consists of a few subsystems which is antenna, Impedance matching, Rectifier (AC/DC converter) and Load. In this paper are focusing about Rectifier circuit and Impedance matching network as shown in Figure 2.4. The main concept of rectifier circuit is to converts the AC captured into a DC power signal. Commonly the rectifier circuit consists of diode and capacitor. In addition, there are three different types of rectifier which are Basic rectifier/Single stage rectifier, Voltage doubler and Voltage multiplier. According to (Rengalakshmi and Brinda, 2016),(Zakaria- et al., 2013) the single stage rectifier circuit design consists of diode that connect in series with load and capacitor for eliminate the noise that smoothen the output. The relation of rectifiers is shown in table 2.3. The voltage multiplier is uses to obtain high output voltage which design in cascaded form of diodes and capacitors. There are many reliable circuit and electromagnetic models for the passive components such inductor and capacitor of the rectifiers. Nonetheless, for the diode, due to its nonlinearity, its model is not easy to construct. The incorrect diode model will create a difference between the simulated and the calculated results of the rectifiers. Therefore, an accurate diode model that can be easily constructed via calculation is very important. Some classical methods for modelling non-linear systems, their corresponding circuit models and drawbacks are presented in this chapter.



Figure 2. 4: RF energy harvesting circuit(Kundu (Datta), Acharjee and Mandal,

2017).

Type of rectifier Structure **Rectifier Topology** Consist of capacitor and a Half-wave rectifier, full **Basic** rectifier diode that connected in wave rectifier. series with load. n'au a Voltage doubler Consists of two capacitor Villard circuit, Grienacher and two diode. AL AVSIA circuit bridge circuit, UNIVERSITI Dickson charge pump voltage-doubler Voltage multiplier Converts RF energy into Villard cascade voltage Dc voltage using a multiplier, Dickson network of capacitors and multiplier, Cockroft diodes. Walton voltage multiplier.

 Table 2. 3: The relation of rectifiers(- et al., 2013).

2.3.1 Basic rectifier topology

The basic rectifier topology is divided into the Half-wave rectifier and Fullwave/Bridge rectifier portion. Normally the half-wave rectifier is a low-efficiency rectifier uses for low power applications. According to (Chuc and Duong, 2015) the halfwave rectifier is a diode and capacitor configuration as shown Figure 2.5. The negative half cycle is blocks the rectifier and appears at zero DC voltage as the diode in reversed biased, serving as an open circuit. In addition, the main important thing for this schematic circuit is the choice of diodes. The Schottky diode (HSM2820) is chosen because have low recovery time and high conversion energy. The maximum RF to Dc power Conversion Efficiency is 40.17% at the input power of 24 dBm with $R_l = 220 ohm$. The power conversion efficiency (PCE) energy of the series rectifier are shown in Figure 2.6. Next, the Bridge rectifier is a high-efficiency rectifier uses for medium and high applications. Consistent with (Marian et al., 2012), (Marian et al., 2011) the bridge rectifier circuit has overcome two diode threshold voltages by using both positive and negative half-wave. It proved that bridge topology is not suitable for low application. The schematic circuit of Full-wave bridge are shown in Figure 2.7. However, the circuit require centre tapping. According to (Kundu (Datta), Acharjee and Mandal, 2017) to measure the input impedance of the rectifier, two centre taps are added to the input and output network. Now when the output charge (RD) is split equal, the current flow between the input and the output center taps will not be distributed. The alternating voltages V1 and V2 are thus to be symmetrical at half the control voltages of a DC offset. These two voltages are similar except for a difference of 180° phases and the AC portion is half the input voltage in all cases. It seems that the input voltage is split in two halves in antiphase by the bridge circuit.

Table 2.4 shown the efficiency of the bridge rectifier. The rectifier efficiency is calculate using equation (2.2) and (2.3)

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.2}$$

$$P_{out} = V_{out}/R_l \tag{2.3}$$



Figure 2. 5: The schematic circuit of the half wave rectifier (Chuc and Duong, 2015).

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Figure 2. 6: The PCE of half wave rectifier(Chuc and Duong, 2015).



Figure 2. 7: The circuit diagram of bridge rectifier(Kundu (Datta), Acharjee and

Mandal, 2017).

Table 2. 4: Efficiency of the Bridge Rectifier(Kundu (Datta), Acharjee and Mandal,

2017).

Input Power	Input Power	Vout (Volt)	Rectifier و دمو
(dBm)	(mWatt)		Efficiency
ONIVER	SITTERNIKAL	0.131 ME	LAKA 3.43
5	3.16	0.502	15.94
7	5.012	0.742	21.96
10	10	1.23	30.26
12	15.84	1.68	35.63
15	31.62	2.58	42.10
17	50.12	3.39	45.86
20	100	5.01	50.20
23	199.52	6.94	48.28

2.3.2 Voltage doubler Topology

Voltage Doubler also known as voltage multiplier circuit that has a voltage multiplication factor of two. Commonly, the circuit consists of two diodes and two capacitors as shown in Figure 2.8. The DC output is equal to the peak-to-peak value of the sinusoidal input. In other words, double the peak voltage value because the diodes and the capacitors work together to effectively double the voltage. According to (Chuc and Duong, 2015), (Song *et al.*, 2015) the function of capacitor C_1 is to store energy element and acts as high-pass filter. The series diode D_1 is rectifying the positive half wave. Thus, the diode D_2 rectifying the negative half wave as the capacitor C_2 store the energy. The operation of circuit improving the maximum conversion efficiency and the power sensitivity. The Schottky diode (HSMS 285x,2820) is widely uses in this schematic design as provide the high switching speed and efficiency (Tudose and Voinescu, 2013). The maximum power conversion energy (PCE) up to 70.06% with input power of 23 dBm (Chuc and Duong, 2015). The calculated efficiency is plotted in Figure 2.9.



Figure 2. 8: Voltage double circuit(Divakaran, Krishna and Nasimuddin, 2019).



Figure 2. 9: The PCE of voltage doubler(Chuc and Duong, 2015).



CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will explain the method and material used to complete this project. Divided into two disciplines that are both project materials and processes. Within the content, it describes the part and, by using the procedure, the flow chart, schematic diagram, circuit diagram and project process will be clarified.

3.2 Material

Material is essential to complement this project and all components are important to be adequate and not less so because each component plays an important role in its own functions. If one of the components is not qualified enough to perform its functions, the circuit will not be able to function properly and there will be a difference in the calculation of the output value (voltage) due to the reason given above. Table 3.1 below shows a list of the main components used for this project. The functions of each material will be presented in Table 3.1, while the quantity required for each component will be shown in Table 3.2.

Material	Function
Diode	Convert AC to Pulsating DC
Resistor	Used to determine the energy delivered to
	the load
Lump elements	To concentrate the power transfer at
	specified frequencies
РСВ	To provide mechanically support and a
	pathway to its electronic components





3.3 Software component

The software component is tools that mainly use for designing the rectifier circuit. It also used to present and collect the output data. This project is completed with software that is explained below.

3.3.1 Advanced Design System

The Agilent Advanced Design System (ADS) is widely used for Research and Design. ADS offers an integrated RF circuit system design environment. Many researchers and designer preferred used ADS to implement and simulate the circuit. In addition, ADS provide a finest class RF simulations especially for harmonic balance simulator. There are few basic steps that need uses for designing circuit in ADS as shown in Figure 3.1. The vital part for the circuit design is to choose the simulation controller because each of the controller have its own function. Example, the S-Parameter analysis is used for matching network (Figure 3.2) and the harmonic balanced is used for power conversion efficiency (PCE).



Figure 3. 1: Quick start for using ADS



Figure 3. 2: S-Parameter analysis

3.4 Rectifier Design

The rectifier purpose is to convert the received RF signal into the correct DC supply voltage through an antenna. The main goal is to convert part of the input power supply to DC for power supply. Basically, there are various form of rectifier which is basic rectifier, voltage doubler and voltage multiplier. In general, the circuit structure consists of four Schottky diodes and a resistor (R_L) as shown in figure 3.3. Positive cycle involves D1 and D3 diodes which are in forward biased. On the other hand, when it involves negative cycles, D2 and D4 are in forward biased. Therefore, D2 and D4 allows current begins to flow through the them when they begin to operate. Next, a capacitor is used for the rectifier circuit to reduce the ripple voltage by acting as a filter. Capacitor polarities must be equivalent to DC output terminals due to their sensitivity to polarity reversal damage



Figure 3. 3: Schematic Diagram of Bridge Rectifier Circuit in ADS201

3.4.1 Rectifier with Impedance Matching

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Low power conversion efficiency (PCE) is due to power leakage during transmission (Divakaran, Krishna and Nasimuddin, 2019). The impedance matching network is designed to provide maximum power when the load is matched to the line and the power loss in the feed line is minimized. The basic concept of impedance matching is to position it between a load impedance and a transmission line. Moreover, it provides maximum power transfer when $Z_{in} = Z_0$. Ideally, the feature of impedance matching is lossless and prevents excessive power loss. There are several factors selection for matching network as below:

Table 3. 3: Factors selecti	on for matching network.					
A.W.						
Factors	Explanation					
Complexity	The simplest design satisfies the					
	necessary requirements is preferable.					
Bandwidth مالسبيا مال	Ideally, any form of matching network					
	will give a perfect match at a single					
UNIVERSITI TEKNIKAL	frequency.					
Implementation	Based on the transmission line that has					
	been used, one type of matching network					
	may suffice for others.					
Adjustability	The matching network can be required to					
	adapt to a variable load impedance in					
	certain applications					

There are several types of impedance combination that are L-network, t-network, and π -network as shown in Figure 3.4. But L-combination is the simplest design. The L-

combination requires only two lump components (inductor, capacitor) to react to a transmission line by the arbitrary load impedance. Impedance matching is functioning as low pass filter to reject higher order harmonics. Therefore, it's important for rectifier circuit. In this section, the L- combination for the rectifier design is proposed. It consists of an inductor and a capacitor in the series-parallel configuration as shown in Figure 3.5. Basically, there are two network for z_L inside or outside of 1 + jx as shown in Figure 3.5. The equations to calculate value of L and C as shown below:



 Table 3. 4: Formula to calculate value of Lump elements.



Figure 3. 5: Type of L-section matching.

3.5 Flowchart of Energy Harvesting



Figure 3.6: Flowchart of Energy harvesting.

3.6 Flowchart of Rectifier Circuit Design



Figure 3.7: Flow chart of Rectifier circuit

3.7 **Gantt Chart**

Table 3.4 below illustrate the plans for making the project in the form of Gantt chart. This table shows the steps that were made in making this project. By following the steps accordingly to the Gantt chart, this project can be done and finish smoothly.

	Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Activities																
PSM 1																
Research a	bout			R												
project																
Study of r	ectifier					-	-				4					
topologies	Jak		مل	, le	_	2.	2		ż,	2	w,	~*	: 9			
Research li	iterature		, A	~					- 1		V					
review	NIVER	SIT	T	EK	NIF	(Al	. M	AL	AY	SIA	M	ELA	KA	÷		
Study bloc	k															
diagram &																
flowchart																
Design Red	ctifier															
circuit																
Report wri	ting for															
PSM1																

 Table 3. 5: Gantt Chart

PSM 2															
Design rectifier															
circuit with															
difference load															
impedance															
Design rectifier															
with impedance															
matching															
Fabrication															
Testing and measurement	YSI.	A 42	ANAVA												
Report writing for PSM 2						J					V				
با ملاك	اونيوم سيتي تيكنيكل مليسيا ملاك														

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CHAPTER 4

RESULT AND DISCUSSIONS

4.1 Introduction

This chapter describes the outcome and discusses the results.

4.2 Simulation

Simulation of the RF energy harvesting circuit is shown in this section. This can be achieved with the 2017-ADS. S-parameter analysis is used to align the network and harmonical balanced analysis is used for the RF-DC conversion. Since in ADS, an antenna cannot be generated for feeding the power to the rectifier, the P1 Tone power is used as a source to generates 2 GHz RF waves. Its replicates an antenna, by delivering this wave as the power source.



Figure 4. 1: Bridge topology circuit. 30



Figure 4.2: Time domain signal for rectification.

The rectification is shown entirely in of Figure 4.2. The value doesn't go below zero. If it's below zero, the rectification is not carried out properly because the RF signal blends too much with the DC output voltage.



Figure 4. 3: Simulates reflection coefficient of the Bridge rectifier.

The simulated return loss responses of the Bridge rectifier is shown in Figure 4.3. The rectifier clearly resonates at 2 GHz for a 50 Ω input source.



Figure 4.4: DC output voltage with different input power (dBm).

The DC output voltage is plotted in Figure 4.4. The input power in dBm begins from -40 and increases by 5dB steps until the maximum of 10 while the load resistance is fixed at 100Ω. The DC output voltage graph show the circuit behaves in a non-linear fashion with different values of input power. The maximum output voltage achieved is at 0.293 V when the input power is at 10 dBm. The DC voltage began to inclined sharply at-15 dBm as it moves towards 10 dBm. The minimum DC output voltage of 5.67mV is achieved at -40 dBm signal input. The output DC voltage generated depends on the values of input power values (dBm). The DC output voltage level are 0.057 V at 0 dBm, 0.004 V at -10 dBm and 46.65 mV at -25 dBm. The behavior of the circuit with regards to changing of the load resistance is researched next. It was found that the DC voltage output is increased simply due to the increased load resistance with a constant input power of 10 dBm as shown in Figure 4.5. At the lower load resistance values, the rate of increase in output voltage was higher when compared to change rate at the higher load resistance value. The maximum amount of DC voltage generated is 0.934 V at 100k Ω . As we can see, the graph began to climb from 50 to 500, with a DC output voltage reaching 0.6 V. At a load resistance value above 5k Ω , the rate of change of DC voltage output starts to decrease. In fact, the difference between 10k Ω and 5k Ω was only 0.031 V. Based on this observation, we can safely conclude that a low load resistance value is more practical.



Figure 4. 5: DC output voltage with different value of Load Resistance (dBm).

4.2.1 Rectifier Efficiency

The dc power (P_{out}) and RF power input(P in) are defined as the RF-to-DC conversion efficiencies. Table 3.8 shows the equation used to determine the efficiency (η).



Table 4. 1: Equation for Power Conversion Efficiency.

Figure 4. 6: PCE of Bridge rectifier circuit with different values of input Power

(dBm).

In ADS, the power conversion efficiency (PCE) can be calculated by using the equation (4.3). Figure 4.6 show the conversion efficiency of the Bridge rectifier circuit. The conversion efficiency is measured with a fixed load resistance (100) between 10 dBm and-40 dBm. The maximum efficiency is found at 10 dBm, which is 17.36%. The value of the PCE has started to drop equivalent to the input power values (dBm). The proposed rectifier is capable of generating adequate DC voltage for low RF incident power. This simple rectifier system is effective in designing an RF energy harvesting system. Between -10 dBm and 0 dBm of input power, the conversion is more than 6%. The Minimum efficiency is found at -40 dBm input, which is 0.0002%.

4.3 Summary

In this chapter the result has been analysed and discussed. The Bridge rectifier circuit is not being manufactured due to Covid-19 situations. The simulations results cannot be verified towards measurement value.

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CHAPTER 5

CONCLUSION AND RECOMMEDATION

5.1 Conclusion

The Rectifier is a very important component for energy harvesting circuit. A novel 2GHz Bridge Topology rectifier circuit has been designed, analyzed and discussed. The DC output voltage is determined by the basis of the changing input power values. The PCE is obtained by the measurement of the output voltage. Based on observation, as input power values increased, the DC output voltage value also increased and improved in efficiency. By varying the input power values, the maximum PCE is found to be 17.36% at 10 dBm. Next, the load resistance is changed and simulated with constant input power. As the load resistance increased, the DC output voltage also increased. But the rising rate of DC output voltage started to become flat above the load resistance of 0.9V. Therefore, it is concluded that a low load resistance value is more practical for the intended purpose of RF Energy harvesting.

5.2 Recommendation

The study of rectifier circuits for energy harvesting can be improved by designing various type of rectifier topologies. In order to achieve a high PCE and DC output voltage, a practical drive test must be carried out to determine the optimum

frequency range with their corresponding amplitudes that can be used at any given location. The result from this drive test can be used to design the optimum gain antenna which can be fed into this rectifier circuit. In addition, another possible area of study is the DC output voltage requirement to powering any IoT application.



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