Wireless Electric Concept and Application in a Living Room

by

Mohd Fadzzrul Bin Jusoh

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Dissertation submitted in partial fulfilment of

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Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

(Pn Hanita Binti Daud)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD FADZZRUL BIN JUSOH

ABSTRACT

The exploration of wireless technology nowadays has widened into a bigger area. One of the areas that is currently being researched by companies and universities around the world is supplying power to the electrical appliances wirelessly. The research is being done since the effect of the technology beneficial to both the human and sciences where power can be distributed wirelessly around the globe. This project presents an overview of a design and implementation of Wireless Electric Concept and Application in a Living Room. Research and study is carried out on how signal and energy in the air can be tapped and converted into useful energy which later can be used to supply power to electrical appliances. The approach of this work starts by harvesting Radio Frequency (RF) signal that is available in the air using RF energy harvesting circuit. This circuit collects or harvest energy in the air and converts them into electricity. It is done by using the antenna to capture the RF energy and the charge-pump circuit to convert and magnify the input signal in AC to larger output in DC. This DC output is then used to power low-voltage equipments in the living room. Simulation work using PSPICE full edition was done to develop the concept and later was used as guidelines in developing the prototype.

ACKNOWLEDGEMENT

Alhamdulillah, praise to Allah the Almighty for giving me the strength, motivation and guidance in completing this Final Year Project. Under His blessing, this project has been completed successfully.

My deepest gratitude goes to my Final Year Project Supervisor, Puan Hanita Daud for guiding me throughout this project. This project wouldn't be in success without her support, advices, suggestions and guidance for every obstacles and problems that was faced during the duration of the project. It is a pleasure to work under her supervision.

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ABBREVIATIONS

AC	Alternating Current
AM	Amplitude Modulation
ANSI	American National Standards Institute
cm	Centimetre
DC	Direct Current
F	Farad (unit)
FCC	Federal Communication Commission
FM	Frequency Modulation
H	Henry (unit)
IEEE	Institute of Electrical and Electronic Engineers
ISM	Industrial-Scientific-Medical
MHz	MegaHertz
RF	Radio Frequency
V	Volt
Wi-Fi	Wireless Fidelity

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Wireless technology is currently being used in many applications all around the world and have a great influence in our daily life, ranging from satellite used on the space to the commonly use hand phone and computer communication, all are utilizing the technology.

Recently, there are efforts and researches being done by companies and universities to develop an application of supplying power to the electrical and electronic equipment using wireless power transmission technology. The approach to this new technology is warmly welcomed by famous companies around the globe like Philips, Toshiba, Sony, Nokia, and others, due to the fact that the technology will bring a lot of benefit to the users, beside the company themselves. Even though the concept is still not being introduced widely to the market but this technology will give high impact to our daily life once it is introduced. By removing the power cable, any accident that is commonly related to the cable like electrical shock and cable-pulling incident (normally by small children) can be avoided. In term of room design and decoration, the technology is a huge advantage since there is no more need to place the electrical appliances near the power cord. The appliances can be located anywhere in the room thus make the design job easier. Besides that, it reduces the cost of manufacturing which will result in lower price of equipment.

Wireless energy transfer or wireless power transmission is the process that takes place in any system where electrical energy is transmitted from a power source to an electrical load, without interconnecting wires. Wireless transmission is ideal in cases where instantaneous or continuous energy transfer is needed, but interconnecting wires are inconvenient, hazardous, or impossible. Though the physics of both are related, this is distinct from wireless transmission for the purpose of transferring information (such as radio and television), where the percentage of the power that is received is only important if it becomes too low to successfully recover the signal. With wireless energy transfer, the efficiency is a more critical parameter and this creates important differences in these technologies.

Except for RFID tags, wireless power transmission over room-sized or community-sized distances has not been widely implemented. Rightly or not, it has been assumed by some that any system for broadcasting energy to power electrical devices will have negative health implications. However, with current researches and developing technologies, the wave produced are safe and within the acceptable range, making it no more dangerous than being exposed to radio waves.

The wireless electric concept has become an interesting topic to modern technologies nowadays where all aspects of communications are implemented wirelessly. This concept may be used as an alternative energy supply especially to the current situation where production of energy is very much dependant to oil and gas. As the current trend shows that the price of oil and gas keep on increasing this alternative is worth to be considered. This concept also may be expanded to reduce our dependency on electric supply especially to the area where the electric supply is always interrupted or for deep sea exploration (e.g. powering the offshore exploration of oil and gas equipment) where powering huge equipment has always been a challenge.

1.2 PROBLEM STATEMENT

In the current world where almost all aspects of life are going to be implemented wirelessly, wireless electric concept is an interesting concept to the modern technologies, where electricity is distributed without interconnecting wires. This concept can be considered as a new alternative energy supply especially to the small-powered electrical and electronic equipments. Exploring the concept of wireless electric, new approaches can be developed in order to utilize the concept economically and user-friendly.

The purpose of this project is to make a research on a suitable concept of wireless electric transmission in a living room. The concept will be applied to power low power electrical appliances such as charging rechargeable batteries and lighting a lamp.

1.3 OBJECTIVES AND SCOPE OF STUDY

The aim of this project is to explore the concept of wireless technology usage in supplying power to the electrical appliances as a new approach of power distribution.

The specific objectives are as follow:-

- To make a research on a suitable concept of supplying power wirelessly in a living room.
- To design and build an economical and safe working model based on the concept.

The focus of the project will be on supplying power to the electrical appliances in a living room wirelessly by using Radio Frequency (RF) signal and convert it to the electricity. This electricity then will be supplied to the electrical appliances. This is an alternative to the current power cable, since RF signal is safe and widely used in the wireless technology.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 WIRELESS TRASNMISSION

Wireless transmission is ideal in cases where instantaneous or continuous energy transfer is needed, but interconnecting wires are inconvenient, hazardous, or impossible [1]. Though the physics of both are related, this is distinct from wireless transmission for the purpose of transferring information (such as radio), where the percentage of the power that is received is only important if it becomes too low to successfully recover the signal. With wireless energy transfer, the efficiency is a more critical parameter and this creates important differences in these technologies [2].

The use of radio frequencies (RF) for communication is a wireless-related technology that already began in a century ago. It is such a mainstay of modern life that people take it for granted. Radio, television, hand phone, Wi-Fi and Bluetooth, all use RF. RF is one of a general class of energy-carrying waves defined in the electromagnetic spectrum. Other bands are visible light, ultra violet light, x-ray light and cosmic ray.

The application of the concept is the same as the AM/ FM radio, which consist of two parts; transmitter part and receiver part. According to Powercast, a pioneer company that successfully build a working power transmitter based on RF, the transmitter, which is plugged into wall socket and functions in generating and broadcasting safe, low power radio waves, will transmit the power to every receiver in range of the transmitter. The receiver then will receive the signal and convert the signal into DC electricity to supply power to the appliances connected with the receiver. The closer the receiver to the transmitter, the better the power received.

2.2 RADIO FREQUENCY (RF) SIGNAL

Radio frequency signal or RF signal is widely used nowadays especially in communication. There are thousands of radio waves that propagate in the air. However, these radio waves do not interfere with each other because each RF transmission transmits at different frequencies. In fact, each application has been specified to operate at certain range of frequency.

The project prototype will use RF frequency of 915 MHz. The frequency is chosen since it falls under Industrial-Scientific-Medical (ISM) RF band range (902 MHz – 928 MHz), made available by Federal Communication Commission (FCC) for low power and short distance experiment. Besides that, the use of the frequency does not need permission from the authority since it is not being used by other applications such as radio transmission, Bluetooth, hand phone communication and TV telecast [3, 4]. Please refer Appendix I for other application range of frequency.

2.3 ENERGY HARVESTING

In this project, the main concern would be focused on the receiver part instead of the transmitter part. This is due to the fact that the receiver plays the most important role in converting the Radio Frequency (RF) signal to electrical signal that will be used by the electrical appliances. Due to this, the signal-to-electric conversion techniques must be discovered to ease the progress of the project.

As there are a lot of applications in our daily life use RF signal to transmit data, the amounts of electromagnetic energy in the air around us is tremendous. Most of them resulted from radio and television broadcasting. Some of this energy left unused by any application. Thus, a technique called RF energy harvesting emerges.

Energy harvesting is a technique used to collect or 'harvest' any energy in a medium to be converted into other means [5]. In this case, RF energy harvesting circuit will collect unused RF energy in the air and convert it into electricity. For this project, the technique will be used to harvest RF energy from a specific range of frequency [6] instead of wide range of frequency, where the receiver will be designed to only harvest energy from RF signal of 915 MHz.

2.4 VOLTAGE DOUBLER

In energy harvesting technique, the output of the energy harvested is not very high to supply power to the electrical appliances as intended in the project. Due to that, the receiver circuit must consist of an algorithm that can increase the output value of the circuit. This is where the voltage doubler algorithm comes in.

Basically, the receiver circuit will consist of antenna, converter and amplifier circuit. The antenna is used in capturing RF energy in the air while the converter circuit is a circuit that is able to convert input from AC to DC. The amplifier will amplify the DC output value that will be supplied to the electrical appliances.

Voltage doubler is an algorithm that will double the input value at the output, theoretically [5]. Besides, it also functions as a convertor where it converts AC input to DC output (rectifier). In addition to that, increasing in the number of the stages of the voltage doubler circuit will increase the output value. The equation is as follow:-

$$V_{out} = \frac{nV_0 \cdot R_L}{nR_0 + R_L} = \frac{1}{\frac{R_0}{R_L} + \frac{1}{n}} \cdot V_0$$

V_{out}	=	Output voltage
V_0	=	Open circuit output voltage
R_0	=	Internal resistance
R_L	=	Load
n	=	number of stages

However, there is a limit to the number of maximum stages that can be supported. This is due to voltage drop. When there is output current, there is also an AC current through the capacitors, resulting in a voltage drop and a lower input voltage for subsequent stages [7]. The equation for voltage drop is shown below:-

$$\Delta U = \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n\right) \quad \text{where}$$

ΔU :	voltage drop
I :	output current
f :	input frequency
C :	capacity of caps
n :	# of stages

CHAPTER 3
METHODOLOGY

3.1 METHODOLOGY

The development of the project adopts the methodology flow depicted in Figure 1 below:-

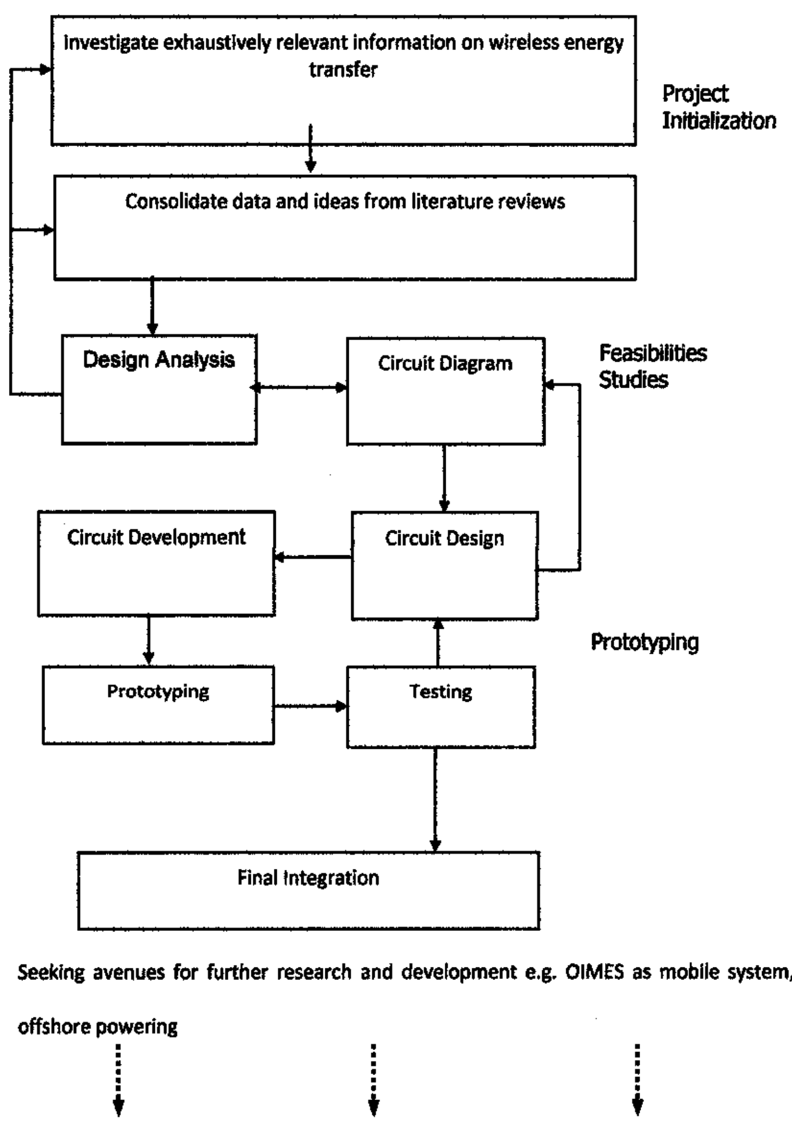

Figure 3.1: Project Development Phase

3.1.1 Project Initialization

3.1.1.1 Document Research

In achieving the objectives on the suitable concept of the project, there are various types of research have been done. One of the researches being done is document research. In finding and selecting the most suitable and feasible concept, there are many documents that have been viewed, covering from articles, journals, magazine and theses. From this research, the most feasible concept for the project has been discovered. Apart from that, some of the theoretical and calculation examples and guidelines were also gained from this research. This research also has discovered improvement method that can be integrated to the project.

3.1.1.2 Internet Research

Another type of research that has been done in realizing the objectives of the project is internet research. This type of research is used since it is fast and easy to obtain information from all over the world. The purpose of internet research is the same as the document research; to find the most feasible concept for the project and improvement method that can be done. In addition to that, this type of research is beneficial especially in finding the international standards for electromagnetic related appliances which have been set by international bodies like Institute of Electrical and Electronic Engineers (IEEE), American National Standards Institute (ANSI) and Federal Communication Commission (FCC). These standards will be applied in the project, parallel with the project objectives to design a safe working model. (Please refer Appendix II for the standards)

3.1.2 Feasibility Studies

3.1.2.1 Design Analysis and Circuit Diagram

From the research done, the basic concept of the project has been acquired. On top of that, I have discovered some methods that can be applied to improve the performance of the project. From the information of these concepts and improvement methods, the draft circuit of the project prototype has been designed. The design process has considered all the requirements needed so that the circuit is assured to meet the project objective. This draft circuit then will be simulated to check its performances. Any improvement design will be done in parallel with the simulation process.

3.1.2.2 Simulation

Project initialization and feasibilities studies as in phase 1 have been conducted using PSPICE full edition prior to the development of the prototype. This is to provide a feature-rich and fully scalable solution that can later be translated to the prototype. The simulation is done to check the performance of the designed circuit. In addition to that, the circuit design improvement process can be done at the same time. From this simulation, the actual value for each component required can be determined. The results of the simulation will be discussed further in Chapter 4: Result and Discussion.

3.1.3 Prototyping

3.1.3.1 Circuit Development and Prototyping

From the designated circuit in the simulation, the project moves to the next phase which is building the first prototype. This first prototype actually consists of all the components needed in the final prototype. The only difference is that the prototype is developed on the bread board instead of on the printed circuit board (PCB). This is purposely done since the main purpose of this prototype is to check the performance of the design. In other words, this prototype will undergo trial-and-error phase, where maybe there will be some modification need to be done to the prototype.

3.1.3.2 Testing

In testing phase, the performance of the prototype is observed carefully. There are various tests that have been done in order to test the performance of the voltage doubler circuit. Besides that, the testing phase also includes the RF energy harvesting test. The purpose of the test is to measure the performance of prototype in harvesting electromagnetic energy (RF energy) in the air.

3.1.4 Final Integration

After the entire tests have been done with the value and type of components has been fixed, the prototype then was upgraded to PCB as the final stage of the project.

3.2 PROJECT PROGRESS

The project has progress according to the plan. Although there are some problems in the middle of the project progression, the problems have been solved and the project is back on the track. Please refer Appendix III and Appendix IV for Project Milestone and Project Gantt chart, respectively.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 DATA GATHERING AND ANALYSIS

The data and information regarding for the design of the circuit generally is from the theoretical part, which involves some calculations. Other information in designing the circuit is observed from the simulation and prototype tests results.

4.1.1 Calculation Part

4.1.1.1 Length of Antenna

$f = 915$ MHz

$T = 1/f = 1.0928 \times 10^{-9}$ s

$T/4 = 0.2732 \times 10^{-9}$ s

$L = c \times T/4, \quad c = 3 \times 10^{8}\ ms^{-1}$

$= (3 \times 10^{8}\ ms^{-1}) \times (0.2732 \times 10^{-9}\ s)$

$= 0.08196\ m \approx 8.20\ cm$

4.1.1.2 Resonator

$LC = 25330.3/ f^2, \qquad f = 915$ MHz

$LC = 25330.3/ (915)^2$

$= 27.6834$

Considering $L = 1\ \mu H$,

$C = 27.6834/ L$

$= 27.6834/ 1$

$= 27.6834$ pF

For the explanation of the calculation, please refer Appendix V

4.2 RESULT

4.2.1 Simulation

These results are the simulation results of the receiver circuit. The simulation is divided into two parts; the performance part and the improvement part.

4.2.1.1 Performance Part

The aim of performance part simulation is to check whether the proposed circuit can produce the desired output. It is also done to predict the output voltage as the number of stages increases.

The results of the simulation are shown below.

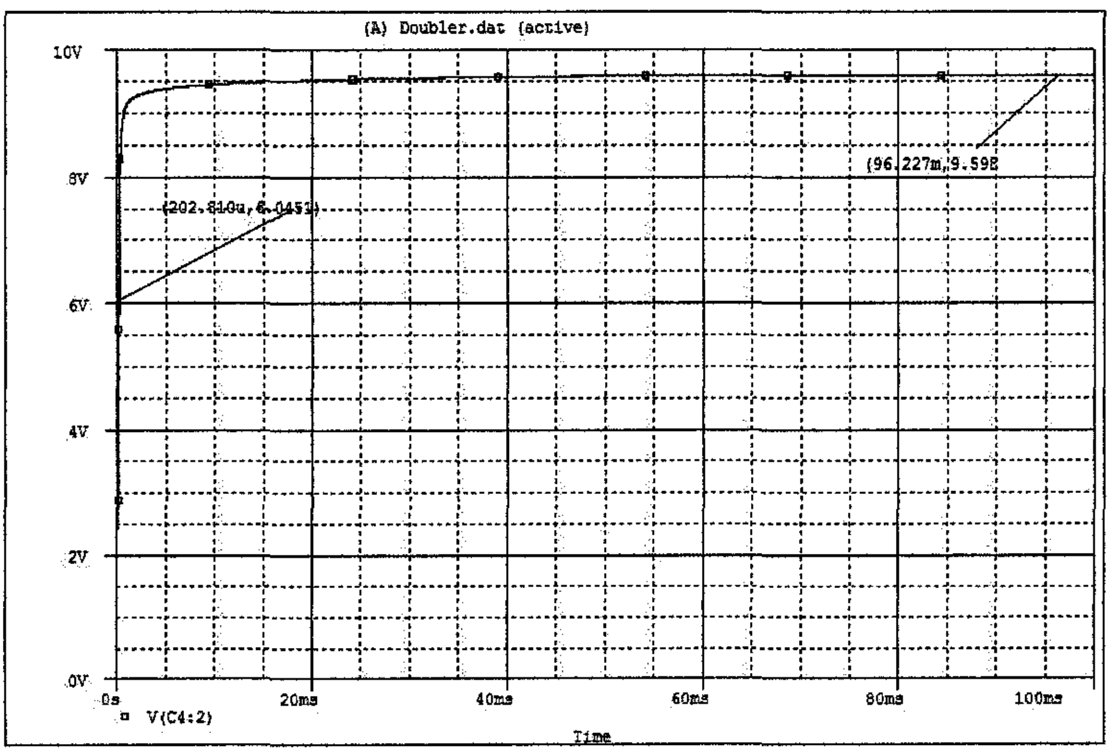

Figure 4.1: Output of Single Voltage Doubler Circuit

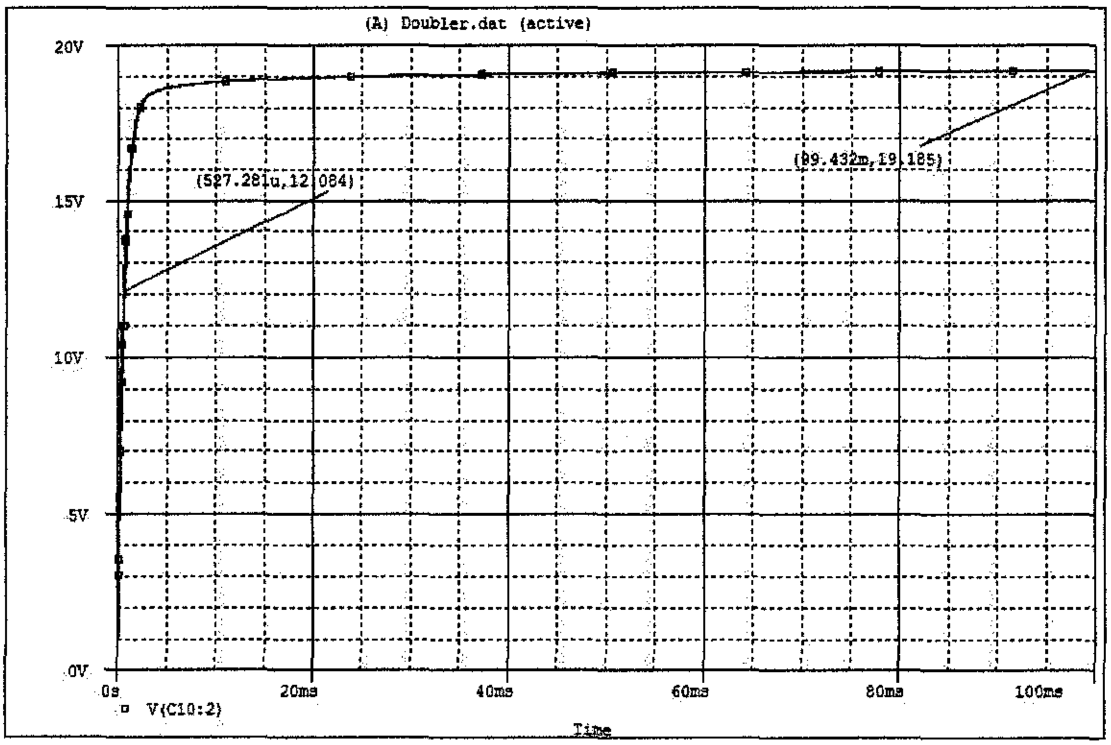

Figure 4.2: Output of 2-stages Voltage Doubler Circuit

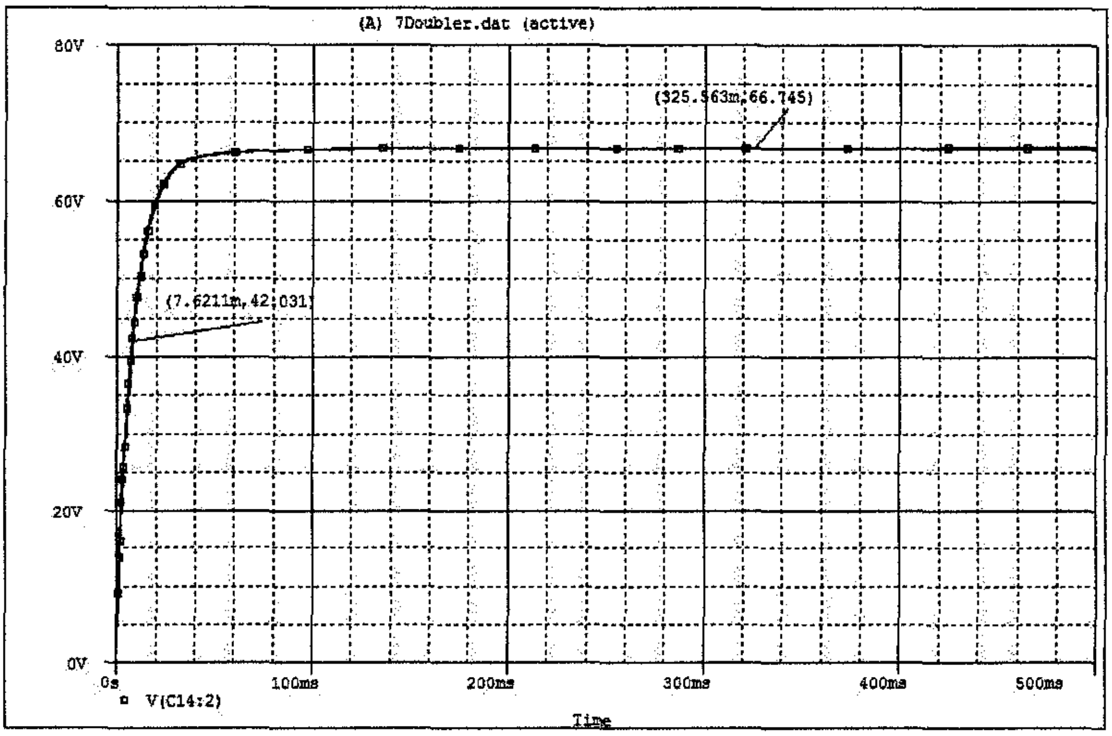

Figure 4.3: Output of 7-stages Voltage Doubler Circuit

4.2.1.2 Improvement Part

For improvement part simulation, there are some tests done to check the performance and to improve the output of the circuit. The tested circuit is shown below:-

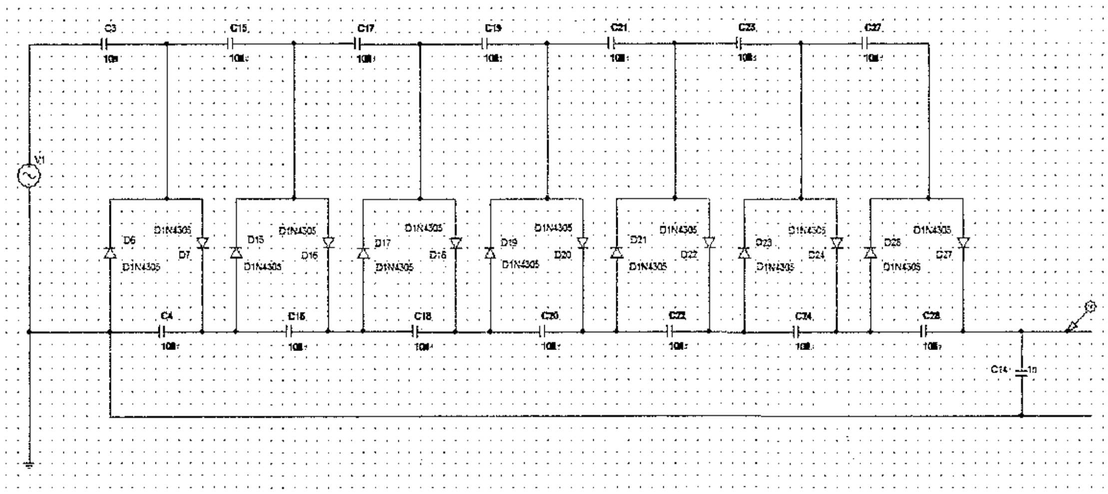

Figure 4.4: 7-stage Voltage Doubler Circuit

The conditions of the circuit are as follow:-

Input Voltage	: 5 V
Frequency	: 10 kHz
Stage Capacitor	: C3, C4, C15, C16, C17, C18, C19, C20, C21, C22, C23, C24, C27, C28
Output Capacitor	: C14

There were three tests being conducted:-

- Test 1: To compare the output performance between circuit that use same value of capacitor in each stage and the one with different value of capacitor in each stage
- Test 2: To find the best stage capacitor value
- Test 3: To determine the optimum value of output capacitor

Some of the results are shown in the next pages. For other simulation results, please refer Appendix VI.

Test 1: Stage capacitor (same value versus different value)

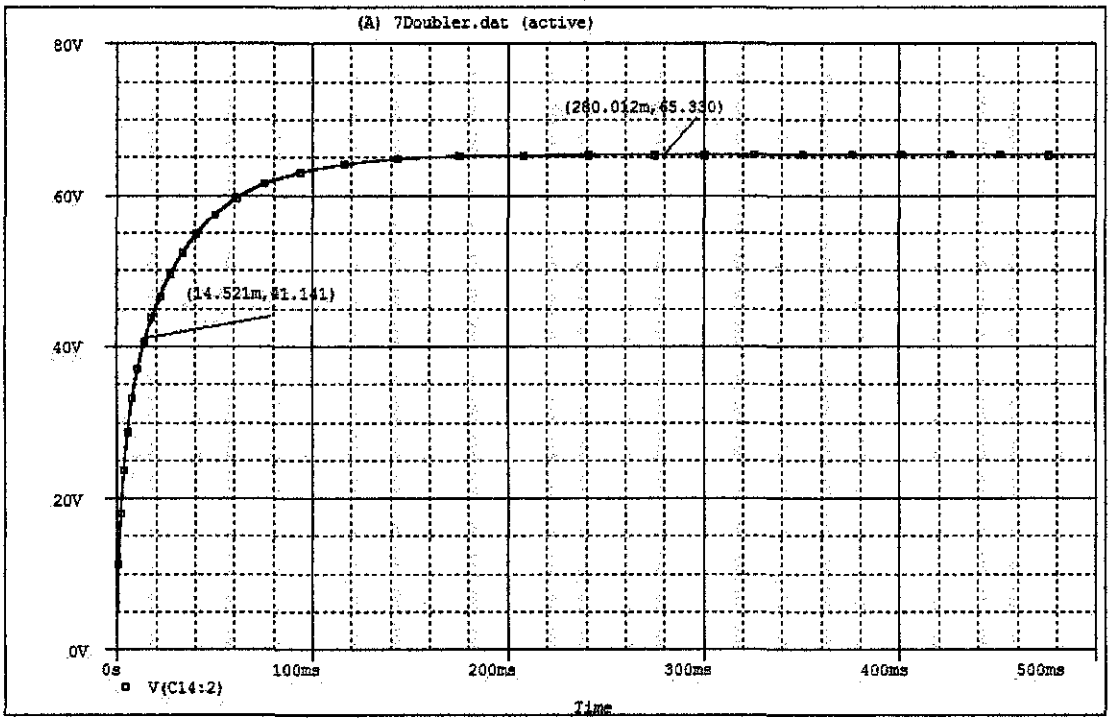

Figure 4.5: Different value of stage capacitor

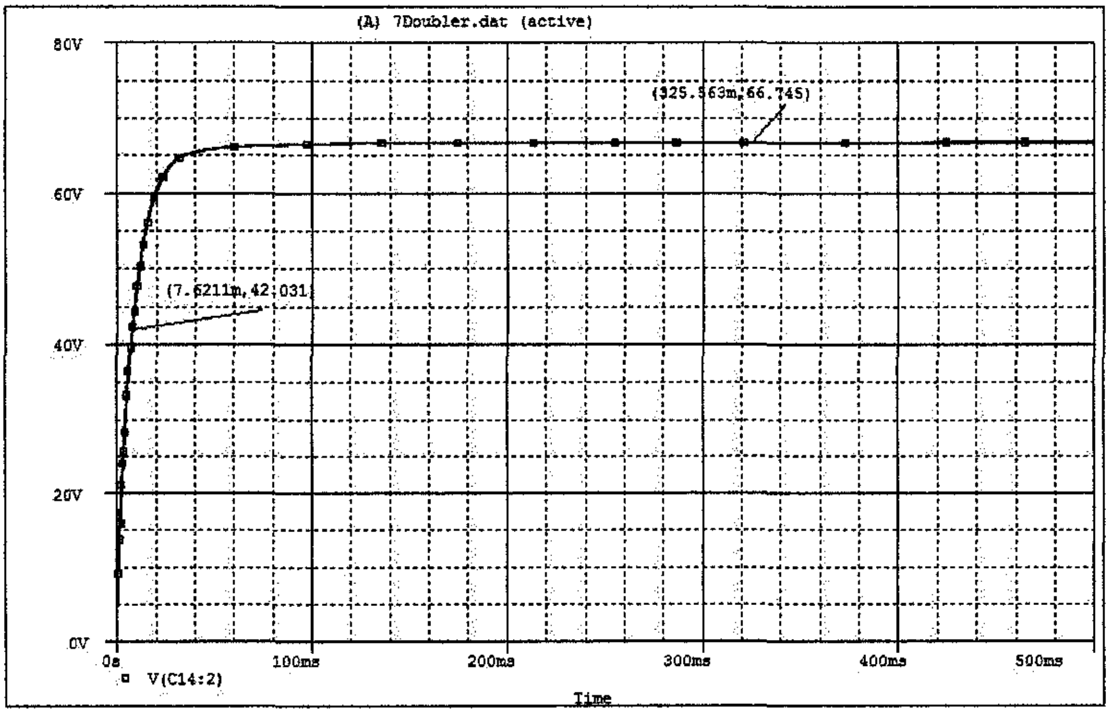

Figure 4.6: Same value of stage capacitor

Test 2: Stage capacitor (different value)

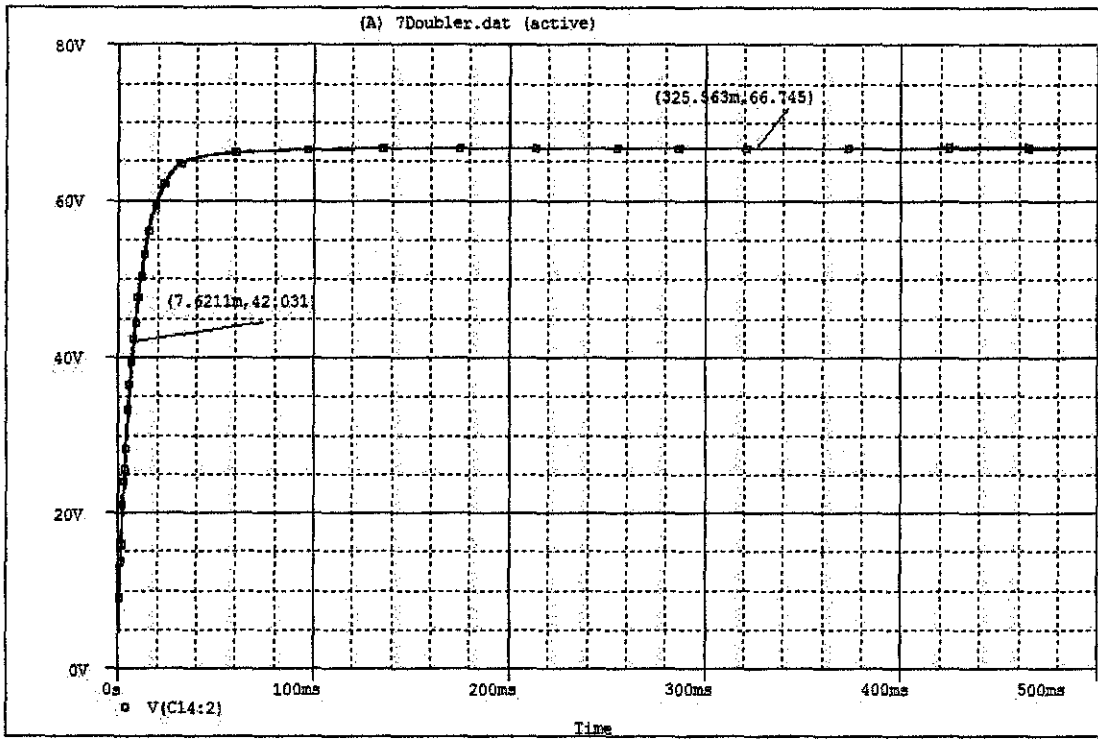

Figure 4.7: Capacitor value = 10 nF

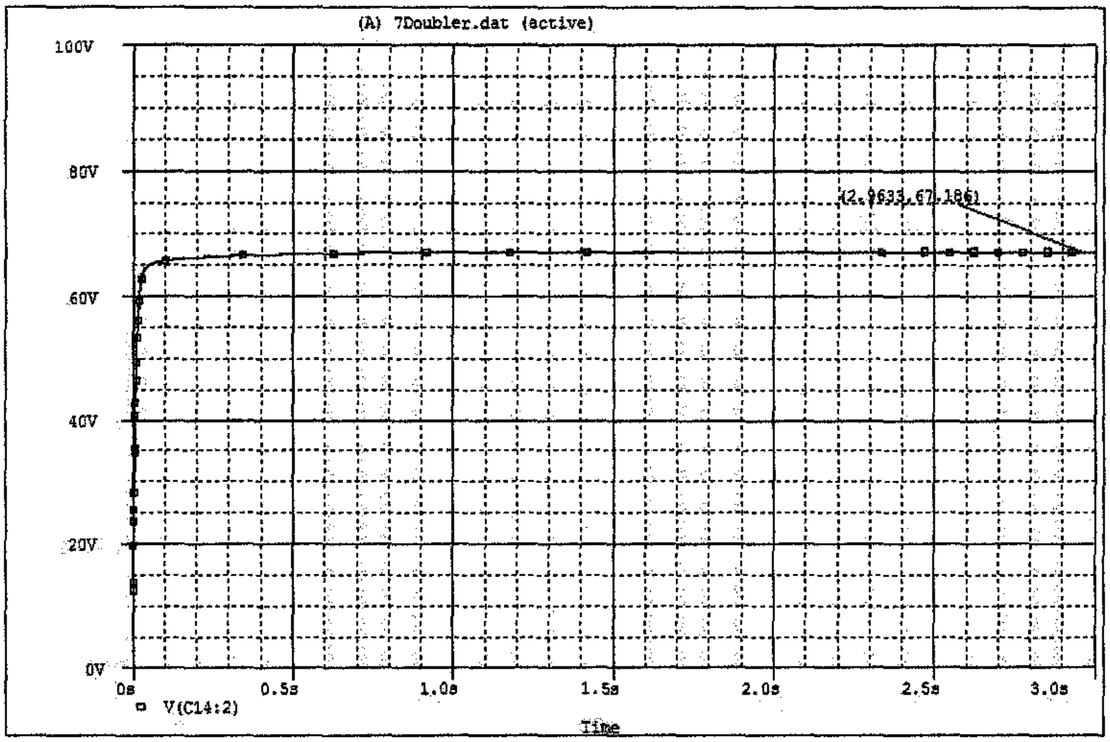

Figure 4.8: Capacitor value = 100 nF

Test 3: Output capacitor

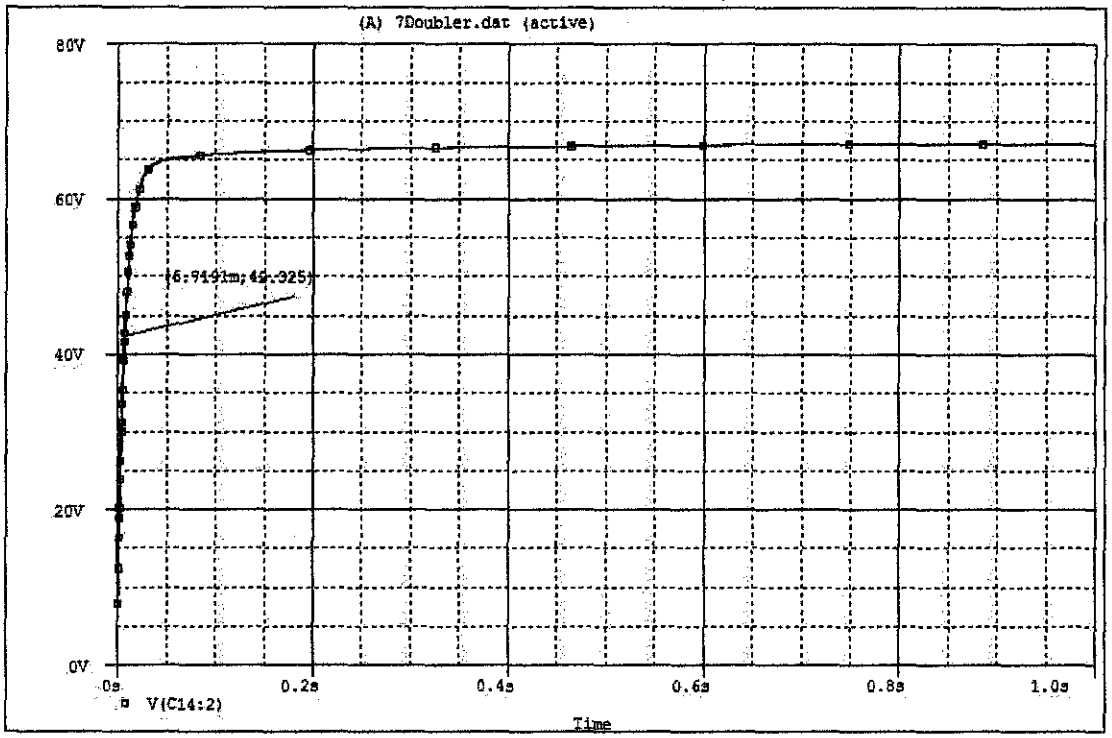

Figure 4.9: Output capacitor = 1 nF

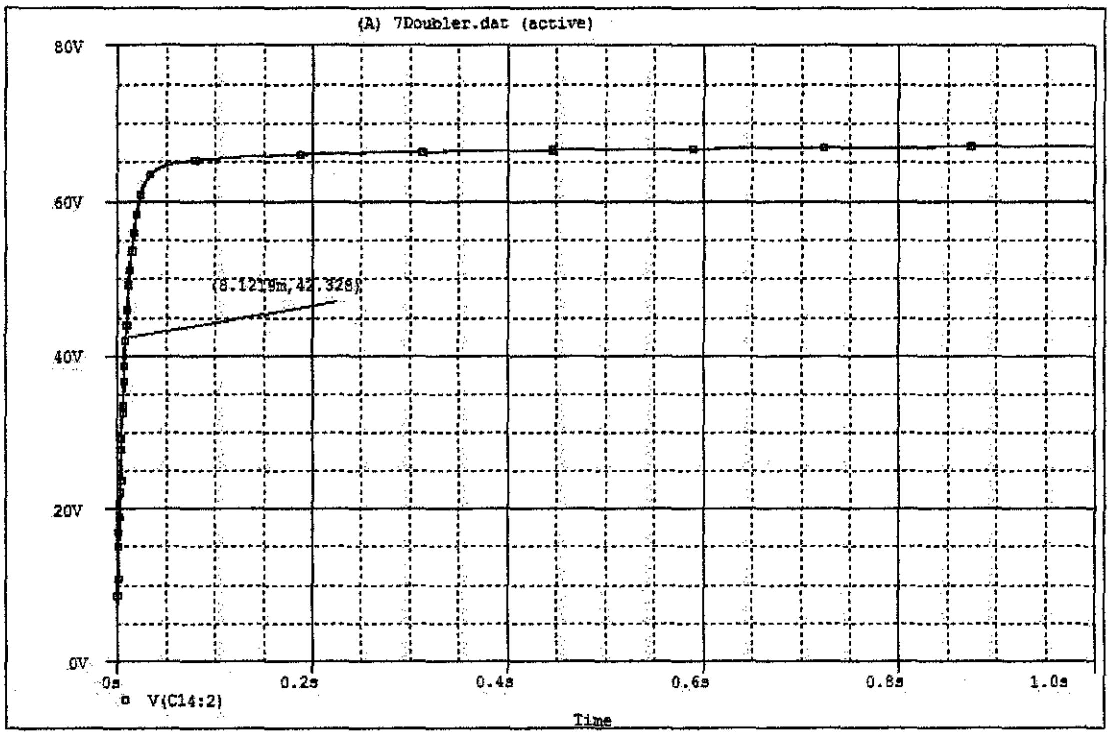

Figure 4.10: Output capacitor = 10 nF

Test 1: Stage capacitor (same value versus different value)

Table 4.1: Result of Test 1 (Improvement Part)

Stage capacitor value	Output Voltage (V)	Rise Time (s)
Same value (10 nF) for each stage	66.75	7.62m
Different value (0.1 nF to 10 nF) for each stage	65.33	14.52m

Test 2: Stage capacitor (different value)

Table 4.2: Result of Test 2 (Improvement Part)

Stage capacitor value	Output Voltage (V)	Rise Time (s)
1 nF	63.50	19.04m
2.2 nF	65.40	12.22m
4.7 nF	66.32	9.41m
10 nF	66.75	7.62m
22 nF	67.05	-
47 nF	67.16	-
100 nF	67.19	-

Test 3: Output capacitor

Table 4.3: Result of Test 3 (Improvement Part)

Output Capacitor Value	Rise Time (s)
1 nF	6.72m
10 nF	8.12m

4.2.2 Prototype

These results are the results of prototype testing phase. The testing phase is divided into two parts; the receiver performance test and energy harvesting test.

4.2.2.1 Receiver Performance Test

In this testing phase, the performance of the prototype is observed carefully. The first test was to test the performance of the voltage doubler circuit. In doing this, the input of the receiver is connected to the ac power supply to get the AC voltage. The result of the test is shown below:-

Table 4.4: Voltage doubler performance

Number of Stage	**Input Voltage (V)**	**Output Voltage (V)**
1	3.0	7.1
2	3.0	13.2
3	3.0	13.1
4	3.0	12.6
5	3.0	12.4

Based on the result above, it could be observed that the voltage doubler did not perform as it should be. The maximum number of stages that it could support is only two. Re-examining the components, have shown that the problems were sourced from the capacitor where its voltage rating is about 12 V.

Knowing the source of the problem, all the capacitors were changed to the electrolytic-type capacitor with the value of 1 micro-Farad with voltage rating of 50V.

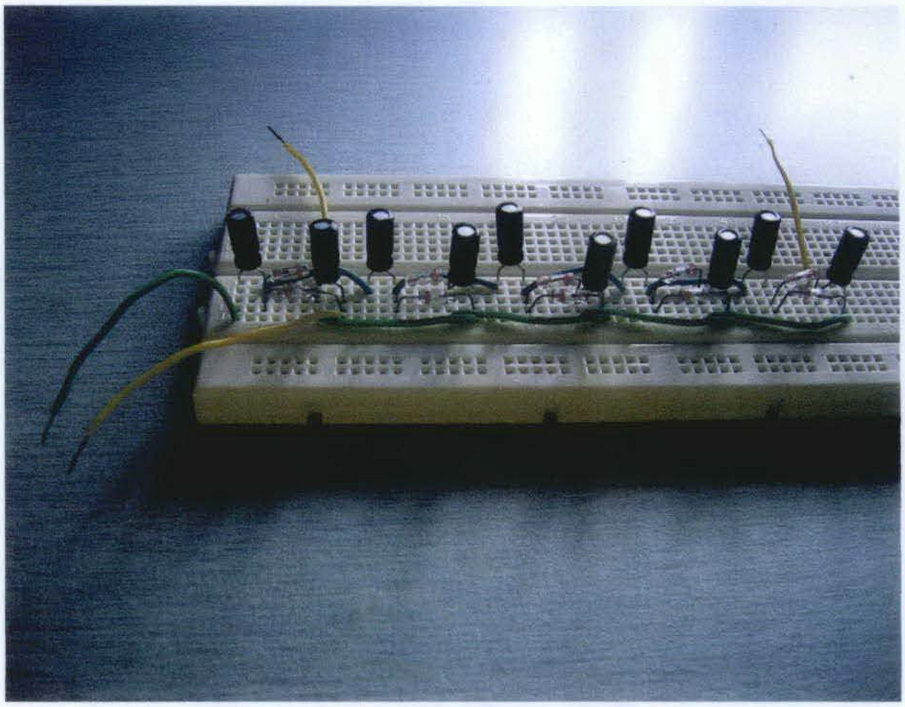

Figure 4.11: Prototype receiver with new electrolytic-type capacitor

New Capacitor

Value : 1 μF

Voltage Rating : 50 V

The performance test of voltage doubler circuit was done again. The results are shown below:-

Table 4.5: Voltage doubler performance with new capacitor

Number of Stage	Input Voltage (V)	Output Voltage (V)
1	3.0	9.5
2	3.0	18.6
3	3.0	25.3
4	3.0	32.7
5	3.0	36.4

Based on the result, the new design looked promising. The supported stage is up to five stages. Although the increment of the output voltage was decreasing, it is acceptable since the decrement have been predicted theoretically.

Continuing from the current design, the number of stages was increased to eight stages to test whether the pattern of the output voltage continued. The result is shown below:-

Table 4.6: Voltage doubler performance for 6, 7 and 8 stages

Number of Stage	**Input Voltage (V)**	**Output Voltage (V)**
6	3.0	36.9
7	3.0	35.7
8	3.0	32.3

Based on the result, it showed that the highest output voltage could be produced from 6-stages voltage doubler instead of 7-stages and 8-stages voltage doubler. Starting from the 7-stages design, the output voltage was decreasing. Re-examining the circuit design and the theory of voltage doubler, the source of the problems was indentified. This will be discussed later in discussion part.

To solve this problem, there are some steps suggested needs to be taken:

- Change the germanium diode to Schottky diode, 1N5817/ 1N5818/ 1N5819. This is suggested to amplify the input into a better output since Schottcky diode is a rectifier diode. By amplifying the input into higher output, it is predicted that the voltage drop would be lowered and the number of stages could be increased.
- Solder the components onto circuit board instead of plugging the components into the breadboard. This is suggested to minimize the effect of internal resistance in the breadboard thus increasing the output value.

Based on the previous test result, it was suggested that the diodes were replaced with Schottky diode, due to that Schottky diode is a power diode (rectifier diode). By changing the germanium diode to Schottky diode, 1N5819, it is expected that a better output could be produced since the voltage drop could be lowered and the number of stages could be increased. The basic specifications of Schottky diode are as follow:-

Model No : 1N5819

Voltage Rating : 40 V

Current Rating : 1 A

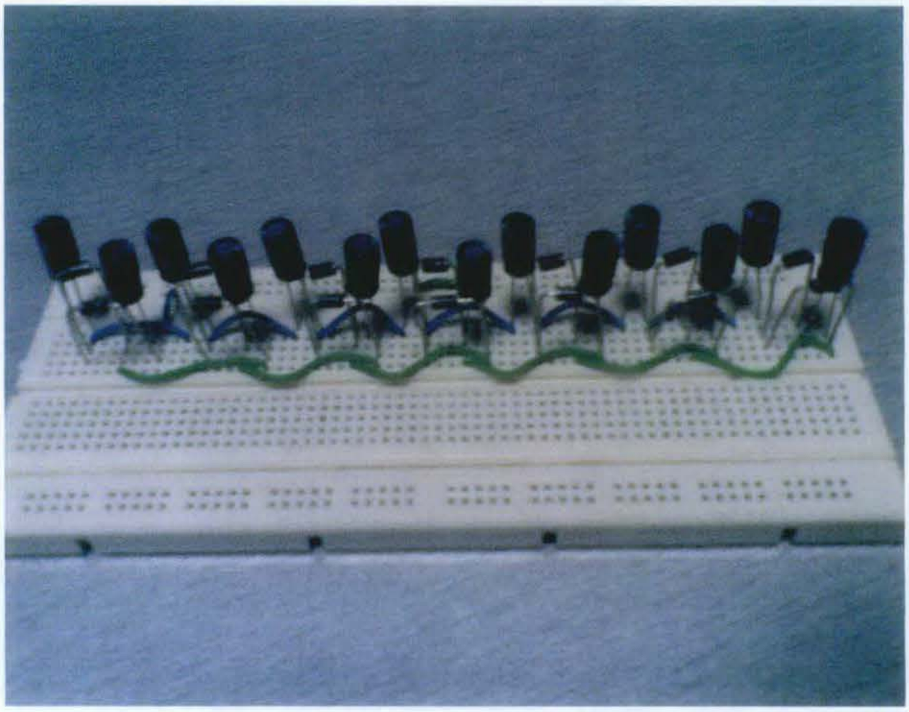

Figure 4.12: Receiver with Schottky Diode (7-Stages Voltage Doubler)

Like the previous circuit, this circuit also tested with 3.5 V, AC input voltage to check its performance as voltage doubler. (Capacitor value is maintained, which is 1 μF) The result of the test is shown below:

Table 4.7: Voltage doubler performance (with Schottky diode)

Number of Stage	Input Voltage (V)	Output Voltage (V)
1	3.5	10.5
2	3.5	18.5
3	3.5	27.7
4	3.5	34.6
5	3.5	38.9

Based on the results above, it could be observed that the voltage doubler did not perform as expected. Same as the previous circuit, as the number of stages increase, the voltage increment is decreased due to voltage drop. From this, it was decided to increase the value of the capacitor to a higher value.

Firstly, the capacitors of 1 μF were replaced with capacitors with the value of 33 μF, 50 V. The test was redone and the result showed a promising result as depicted in table 2 below:

Table 4.8: Voltage doubler performance with new capacitor value (33 μF)

Number of Stage	**Input Voltage (V)**	**Output Voltage (V)**
1	3.5	10.5
2	3.5	21.3
3	3.5	32.1
4	3.5	42.6
5	3.5	53.4
6	3.5	64.1
7	3.5	74.3

Based on the result in table 2, it could be observed that the voltage doubler circuit work better that expected. The increment in voltage doubler stages did not affect the performance of the circuit. By this, it was proven that Schottky diode is suitable for this type of application (rectify and amplify the input voltage). The voltage drop also being lowered thus stage increment could be done without any problem.

In order of testing the performance of the new circuit, the capacitor value was increased again to 330 μF. After replacing all the capacitors, the test was redone. The result is shown below:

Table 4.9: Voltage doubler performance with new capacitor value (330 μF)

Number of Stage	Input Voltage (V)	Output Voltage (V)
1	3.5	10.7
2	3.5	21.9
3	3.5	33.0
4	3.5	43.1
5	3.5	54.1
6	3.5	64.7
7	3.5	74.9

Based on the result above, it could be observed that the performance was about the same as the circuit with 33 μF capacitors. The voltage increment was not very significant. This is maybe due to that the output voltage has reached its maximum value for each stage.

From the result of all tests, it was suggested that the receiver prototype would used the following components:

- Schottky Diode (1N5819) – the performance of the diode have been proven in amplifying and rectifying the voltage
- 33μF capacitor – The 33μF capacitor is preferred compared to the 330μF since the performance is about the same. Besides, the size of the capacitor is smaller and this is crucial in minimizing the overall circuit size.

4.2.2.2 Transmitter

Basically for the transmitter part, there will be two phase. The first phase is to purchase the transmitter in the market and used it to check the performance of overall prototype. The second phase of transmitter part concern on designing the transmitter based on specification needed.

For the first phase, a transmitter had been purchased where it could transmit a 300 MHz signal. Initially, a 915 MHz transmitter was preferred. However, due to unavailability of the transmitter in local market, another transmitter was purchased. This transmitter would function as performance checker of overall prototype as well as become the base design of the designed transmitter (phase two).

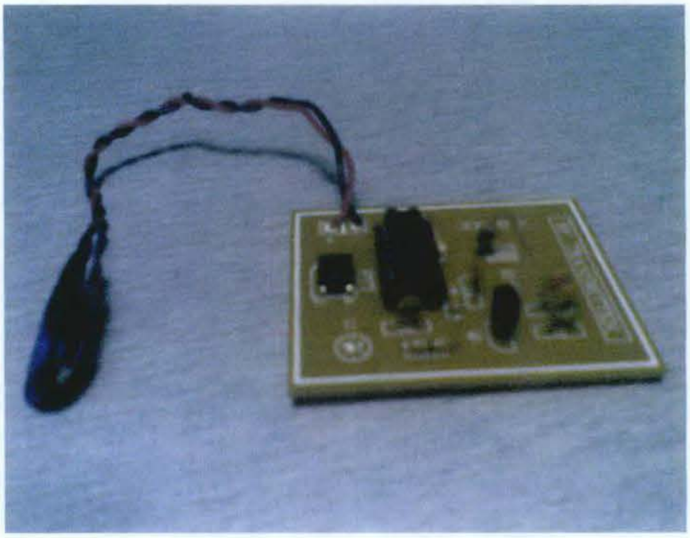

Figure 4.13: 300 MHz Transmitter

The transmitter had been tested and it worked as it should be. However, there was a drawback of using this transmitter. As observed from the figure 2, there was no external antenna, since the antenna was printed at the back of the board (Printed Antenna). The disadvantage of this type of antenna was that, it is a directional antenna. It means that the receiver antenna should be in line with the transmitter antenna to receive its signal. However, this was not a big issue since the transmitter was used only as a performance checker.

It is suggested that an external antenna can be attached to the transmitter so that the signal can be transmitted in various direction (Omni-directional antenna).

4.2.2.3 Energy Harvesting Test

Another test conducted was energy harvesting test. The test was done to test the performance of the prototype in harvesting electromagnetic energy in the air. In this test, the antenna was connected to the input of the prototype, replacing the AC power supply. The output of the receiver was connected to the voltmeter to measure the output voltage that could be produced.

There were two tests being carried out. The first test was done using the first-built receiver circuit which was using germaium diodes. The second test was done using the redesigned receiver circuit which was using Schottky diodes. For each test, there were two type of tests being done; harvesting ambient electromagnetic energy and harvesting energy from transmitter.

Figure 4.14: Receiver Prototype

Table 4.10: First Part (Energy Harvesting Test) Result

Source	Output Voltage (V)
Ambient electromagnetic energy	0.002
Ambient electromagnetic energy (properly grounded)	0.120
RF signal from transmitter	0.200
RF signal from transmitter (properly grounded)	2.100

From the first test (using receiver with germanium diodes), it was concluded that the antenna need to be grounded properly, as well as the circuit. This is because without proper grounding, the gain of the antenna become lower, thus reducing the amount of energy harvested. This is proven in the test where a proper grounding antenna would produce a far better output compare to antenna without grounding. In this test, human body and metal material equipment/ parts become the source of grounding.

In order of improving the energy harvesting process, two steps are suggested:-

- A proper grounding should be done to the antenna to improve its performance. The method of proper grounding should be researched to minimize its size so that the prototype would be optimum in size and performance.
- Another step that could be taken is to use an antenna that does not need grounding at all to operate optimally. An example for this type of antenna is dipole antenna. However, there is a drawback to this step where the length of the antenna would be longer than the antenna with grounding method.

Figure 4.15: The antenna (Monopole antenna)

The suggestion from the first part was integrated in the second part of the test. In the second test (using receiver with Schottky diodes) of energy harvesting test, for the first phase, we connected the antenna to the new receiver circuit (the circuit with schottky diode) and observed its performance in harvesting ambient electromagnetic energy. The result showed that there was no voltage gained (output voltage = 0 V). It meant that the circuit failed to harvest any surrounding ambient energy. Next, the circuit was tested with the signal from the transmitter. The result was still the same; there was no output observed. The only explanation to this phenomenon could be due to the input voltage where the voltage gained from the energy harvesting activity maybe too low for the diode to operate.

From this unexpected result, the receiver circuit was redesigned and the germanium diode was placed back instead of the schottky diode. The redesigned circuit was connected to the antenna and its performance of the first phase was observed. From the voltmeter, it could be observed that this circuit successfully harvest ambient electromagnetic energy. At 4-stages voltage doubler, the receiver managed to produce an output voltage of 0.12V. From this result, we tested the receiver in harvesting signal from the transmitter.

The result of the test is shown below:

Table 4.11: Distance versus Output Voltage (Energy Harvesting Test)

Distance (cm)	Output Voltage (V)
4	2.4
6	1.8
8	1.2

From the result, it showed that the receiver hasd successfully fulfil its requirement in harvesting energy for wireless electric application by producing DC voltage at the output. However, the output gained kept changing due to various factor such as surrounding air, directionality of transmitter antenna and receiver antenna gain.

4.2.2.4 Final Prototype and Application

Using the result from the previous test (energy harvesting test), the final prototype of the receiver was built. This final prototype was tested again with energy harvesting test (harvest energy from signal generated by the transmitter) to make sure it operated as intended.

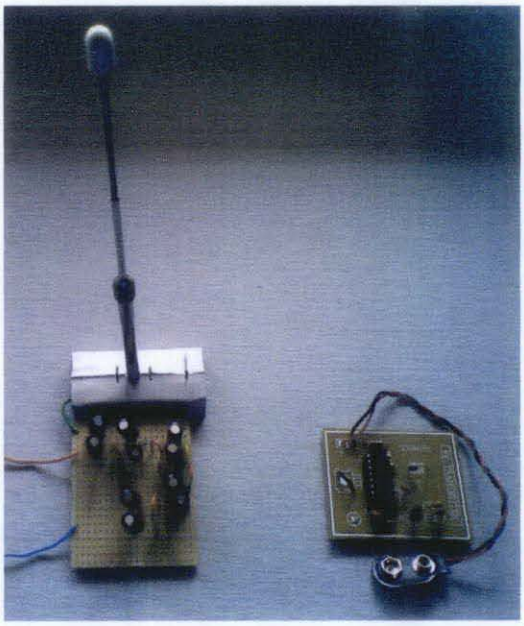

Figure 4.16: Final Prototype (Receiver and Transmitter)

The result for the test is shown below:

Table 4.12: Distance versus Output Voltage

(Energy Harvesting for Final Prototype)

Distance (cm)	Output Voltage (V)
1	5.39
4	3.04
6	2.12

From the result, it clearly showed that the energy of the signal generated by the transmitter had been harvested, rectified and amplified by the receiver circuit to produce DC voltage. In fact, the DC voltage produced was slightly higher than the one obtained with the first prototype.

Continuing from the test, the prototype was tested for daily application. For application part, the DC output of the receiver was connected to a battery charging circuit. This simple battery charging circuit would charge two AA batteries. This circuit was used since it required low DC voltage to operate which would accomodate the output produced by the receiver circuit.

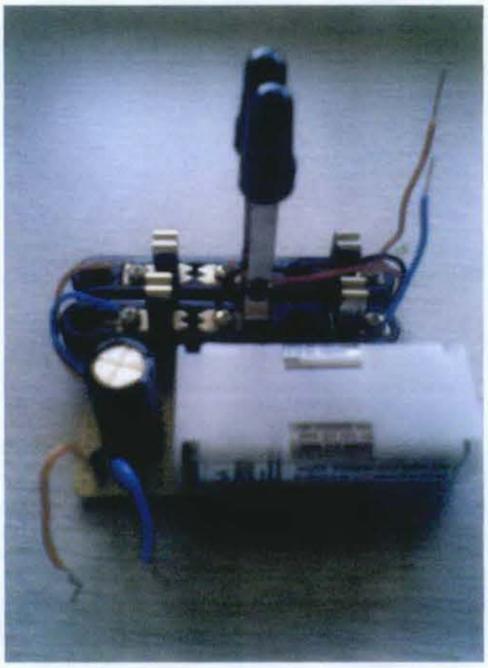

Figure 4.17: Simple Battery Charging Circuit

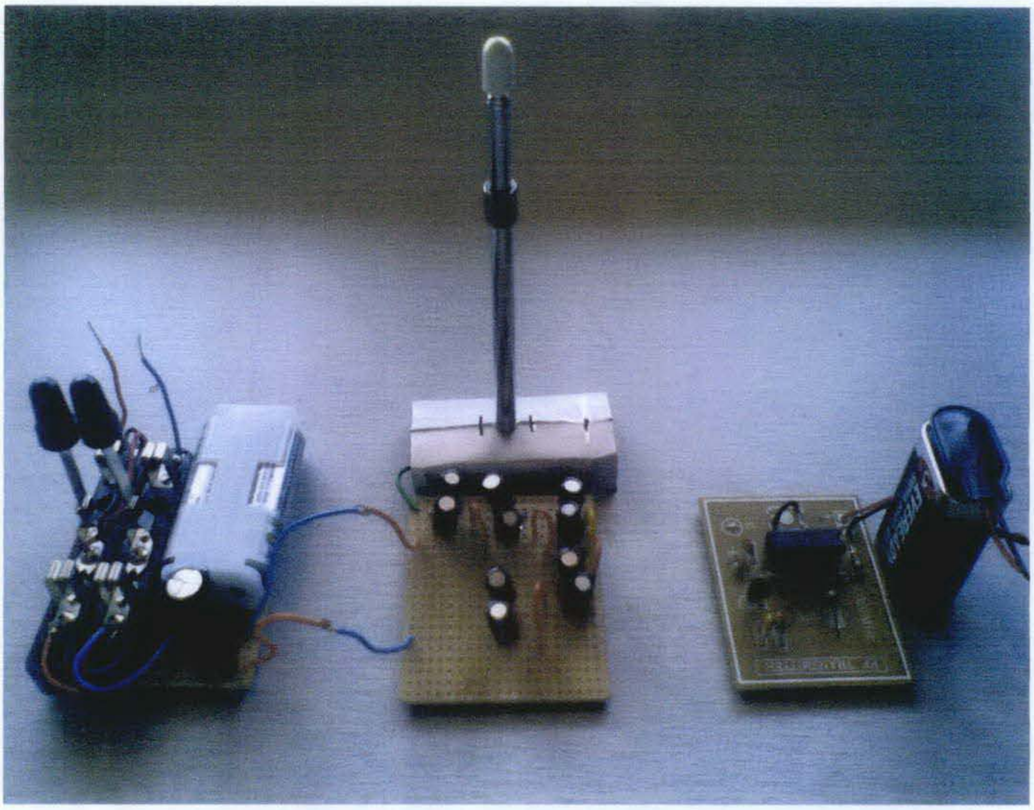

Figure 4.18: Overall Circuit (Charging circuit, Receiver and Transmitter)

Using as a voltage supply for the charging circuit, the battery charging rate was measured. From the observation, the charging rate for the batteries was 0.5 mV per hour. The charged batteries could be used for various application like lighting a small bulb, used in walkman, camera and other low voltage appliances.

4.3 DISCUSSION

4.3.1 Simulation

4.3.1.1 Performance Part

The purpose of this simulation was to check whether the proposed circuit could produce the desired output. For this simulation, the antenna was replaced by AC source since the output of the antenna would be in AC form. The input was set to 5 V for easy reference and observation. From the results of the simulation for a single voltage doubler circuit, it was observed that the proposed circuit had satisfied the requirement as a voltage doubler circuit since the output was about the double of the input. As the number of stages increased, the output value was also increased. From the results, it was also observed that addition of stages would increase the output value about 9 to 10 V. Analyzing from this simulation results, the general equation for determining the output value is stated as follow (as long as the value of the stage capacitor is the same):-

$$V_{out} \approx 0.95\,(N)\,(2\,V_{in})$$

where V_{out} = output voltage

N = number of stages

V_{in} = input voltage

4.3.1.2 Improvement Part

The purpose of this simulation was to determine the value of stage capacitor and output capacitor that would be used in building the prototype. There were three tests being conducted. The first test was to compare the output result (output voltage and rise time) between putting different value of capacitor in each stage (e.g. Stage 1 capacitors = 10 nF, stage 2 capacitors = 4.7 nF, stage 3 capacitors = 2.2 nF and so on) and putting the same value of capacitor for all stages (e.g. stage 1 capacitors = stage 2 capacitors = stage 3 capacitors = ... = 10 nF). Based on the result, it could be observed that circuit with the same value of capacitor for each stage had slightly higher output voltage and faster rise time. This was due to the different charging time between capacitors where the circuit with same capacitor value had the same charging time for each stage while the circuit with different value of capacitor had various charging time which some of them were slower than others.

Continuing from test 1 was test 2 where each sub-test would use different value of capacitor while each stage had the same value. The purpose of this test was to find the best value for stage capacitor that would give optimum result. Based on the results, it could be seen that as the capacitor value was getting higher, the output voltage became slightly higher (about 0.03V – 0.1V increase) and the rise time became shorter. From this, it could be concluded that the higher the capacitor value, the better the result was.

For test 3, the output capacitor was tested with different values. Based on the result above, the capacitor with lower value (1 nF) gave faster output response compared to another value (10 nF). Like the first test, this was due to the charging time of the capacitor where lower value capacitor had faster charging time compared to the higher value capacitor.

Conclusion of the simulation circuit

- Stage capacitor
  - Same value for each stages
  - Higher value give slightly better output (ouput voltage and rise time)
  - Value that would be used = 100 nF
- Output capacitor
  - Lower value give better output response in term of rise time
  - Value that would be used = 1 nF

4.3.2 Prototype

4.3.2.1 Receiver Performance

In receiver performance test, there were various test have been done. The first test was done using 100 nF capacitor. From the result, it could be observed that the receiver did not produce the expected result where the output voltage is around 12 to 13 V only instead of 67 V (from simulation). Checking the condition and the components of the circuit, the source of the problem was due to the rating of the capacitor where the voltage rating is 12 V. From this result, the capacitor was changed to electrolytic-type capacitor (value of 1 microFarad and rated at 50 V)

For the second test, initially the circuit showed a promising result where the output voltage produced was as the expected value. However, by increasing the number of stages to 6, 7 and 8 stages, the output voltage become 'unstable' where the highest output voltage was produced from 6-stages voltage doubler instead of 7-stages and 8-stages voltage doubler. Starting from the 7-stages design, the output voltage was decreasing. Re-examining the circuit design and the theory of voltage doubler, the source of the problems was indentified. It was due to the voltage drop. When there is output current, there is also an AC current through the capacitors, resulting in a voltage drop and a lower input voltage for subsequent stages [6]. The equation for voltage drop is shown below:-

$$\Delta U = \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n\right) \quad \text{where}$$

ΔU : voltage drop
I : output current
f : input frequency
C : capacity of caps
n : # of stages

Due to the voltage drop problem, the germanium diode used in the circuit was changed to Schottky diodes, a type of power diode. With capacitor of previous value (1 μF, 50 V), the receiver circuit was retested. From the result, it could be observed that the output voltage produced was not very high as expected. Considering the condition of the circuit, it was concluded that the problem came from the value of capacitor, where its value maybe not very high to store a large amount of electrical energy. From this, the capacitor value was increased up to 33 μF and 330 μF.

Continuing the test with both values of capacitors (33 μF and 330 μF), the results have shown us the expected result where the output voltage was 75 V. In fact, this value was better than predicted result which is 70 V.

From the result of all test, it could be concluded that capacitor voltage rating, diode types and capacitor values play important role in determining the output value of the receiver circuit.

4.3.2.2 Energy Harvesting Test

In energy harvesting test, basically there were two parts; germanium diode based receiver and Schottky diode based receiver. For each part, there were two tests conducted. The first test was to harvest energy from ambient electromagnetic energy in the air. The second test was to harvest energy from the transmitter.

From the results of all tests done, it could be concluded that the receiver with germanium diode was good in harvesting electromagnetic energy but not very good in amplifying the received signal to its maximum. On the other hand, the receiver circuit with Schottky diode was very good in amplifying the input signal to its maximum value but not well in harvesting electromagnetic energy. The cause of this phenomenon is actually due to the type of diode used. Germanium diode is a small signal diode where it is widely used in application that is related to signal. Schottky diode is a power diode where it is widely used in application that is related to power.

Based on this, it is suggested that a research on combining both type of diode in the receiver circuit should be done so that the advantages from both type of diodes can be gained by the receiver thus realizing the application of wireless electric in our world.

4.3.2.3 Final Prototype and Application

For the application part, the receiver was connected to a simple battery charging circuit. The charging circuit was used to charge 2 AA rechargeable batteries.

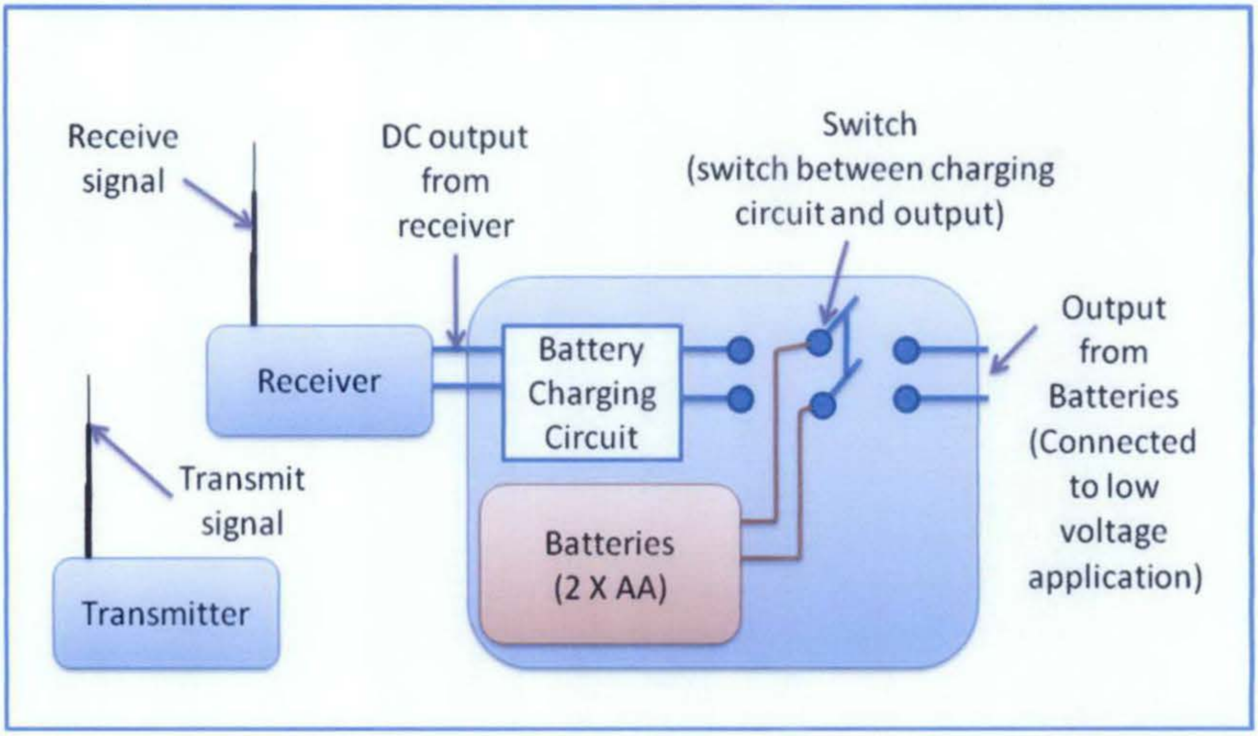

Figure 4.19: Application Part Operation

For the operation of the application circuit, it started with the transmitter transmitting signal to the receiver. The received signal would be amplified and rectified into DC voltage by the receiver. This DC output voltage was connected to the battery charging circuit to charge the rechargeable batteries. A switch was used to switch the connection of the batteries between the charging circuit and output application. During charging process, the switch was connected to the charging circuit. During application, the switch was connected to the output application port for various low voltage application like lighting a low-voltage bulb, rotating a small DC motor and more. In addition to that, the batteries could be used in other low voltage equipment like walkman, MP3 player and camera.

Based on the observation, the charging rate was 0.5 mV per hour. The rate is very low compared to the standard charging rate. The reason for this is due to low DC voltage output produced by the receiver. To improve this, further research should be done especially in integrating both germanium diode and Schottky diode in the receiver circuit. From that, the receiver circuit can harvest the energy in the signal transmitted and amplify it to produce higher DC output.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

For the conclusion, the purpose of this project is to explore a new approach of power transmission to electrical appliances by using RF signal. The objectives functions as benchmarks of the project. Based on the theories stated, researches that have been done gave more focus on the receiver part including the approach used, the design and the improvement research. In addition to that, research also being done on the international standards that should be applied in designing a safe working prototype. The circuit of the receiver has been designed and simulated using PSpice. The results of the simulation become the basis of building the project prototype. Various tests have been done to the prototype including performance test and energy harvesting test. From the result, the prototype has work as intended, which is transferring electricity wirelessly although the value is not very high. Further research and prototype test should be done especially in integrating both germanium diode and schottky diode in the receiver circuit to make sure better output produced in realizing the concept as an alternative energy supply in the future.

5.2 RECOMMENDATION

Below are some recommendations that can be done to improve the project

- Further research on diode

  From the tests done, it could be observed that both germanium diode and Schottky diode have their own advantages and disadvantages. Further research should be done especially in integrating both type of diode in the receiver so that both diode advantages can be optimized by the receiver circuit.

- Circuit minimization

  Circuit minimization can be done after the final prototype has been built. What it means by circuit minimization is that the circuit of the receiver and the transmitter will be minimized as possible. The purpose of this minimization is to reduce the area covered by the circuit as well as lowering the power used by the circuit. From this, the prototype can be designed to fit the market trend nowadays.

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APPENDIX I: RANGES OF FREQUENCIES

- AM radio - 535 kilohertz to 1.7 megahertz
- Short wave radio - 5.9 megahertz to 26.1 megahertz
- Citizens band (CB) radio - 26.96 megahertz to 27.41 megahertz
- Garage door openers, alarm systems, etc. - Around 40 megahertz
- Standard cordless phones: Bands from 40 to 50 megahertz
- Baby monitors: 49 megahertz
- Television stations - 54 to 88 megahertz for channels 2 through 6
- Radio controlled airplanes: Around 72 megahertz, which is different from...
- Radio controlled cars: Around 75 megahertz
- FM radio - 88 megahertz to 108 megahertz
- Television stations - 174 to 220 megahertz for channels 7 through 13
- Wildlife tracking collars: 215 to 220 megahertz
- MIR space station: 145 megahertz and 437 megahertz
- Cell phones: 824 to 849 megahertz
- New 900-MHz cordless phones: Obviously around 900 megahertz!
- Air traffic control radar: 960 to 1,215 megahertz
- Global Positioning System: 1,227 and 1,575 megahertz
- Deep space radio communications: 2290 megahertz to 2300 megahertz

APPENDIX II: INTERNATIONAL STANDARDS

Currently, there is no specific rules and regulation for power-line electromagnetic fields (electromagnetic field generated by electrical power transmission). However, the standard can be derived from the regulations ruled out for RF exposure.

The main characterizations in RF energy are its frequency and wavelength. Based on the electromagnetic spectrum, RF waves have range from 3 kHz up to 300 GHz and the wavelength differ for each frequency based on the equation: speed of light (c) = Frequency (f) X wavelength (λ). Fortunately, RF waves are among the non-ionizing waves.

In measuring electromagnetic field, one of the most commonly unit used is 'power density'. It is used to measure a field that is far enough from the source. Power density is described as power per unit area (e.g. mW/cm^2, W/m^2).

Another criteria used to measure the RF energy is Specific Absorption Rate or SAR. It is used to measure the quantity of RF energy that is being absorbed by human body and the potential harm that it can bring. It is usually expressed in units of watts per kilogram (W/Kg).

Besides that, the exposure time to RF radiation is another main criterion. It is defined as a recommended time limit over an exposure. The concept is, exposure level over time must not be greater than the allowable exposure limit (equal to power density) multiply with the specified average time. As long as the exposure is not too high or average, it is allowed to extend exposure time limit for a short period.

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-1.34	614	1.63	(100)*	30
1.34-30	824/f	2.19/f	$(180/f^2)$*	30
30-300	27.5	0.073	0.2	30
300-1500	--	--	f/1500	30
1500-100,000	--	--	1.0	30

f = frequency in MHz *Plane-wave equivalent power density

Source: OET Bulletin 65, Edition 97-01, August 1997

Specific Absorption Rate (SAR)	
Occupational/Controlled Exposure (100 kHz - 6 GHz)	**General Uncontrolled/Exposure (100 kHz - 6 GHz)**
< 0.4 W/kg whole-body **≤ 8 W/kg partial-body**	**< 0.08 W/kg whole-body** **≤ 1.6 W/kg partial-body**

Source: OET Bulletin 65, Edition 97-01, August 1997

APPENDIX III: PROJECT MILESTONE

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continue	■	■	■												
2	Submission of Progress Report 1				●											
3	Project Work Continue				■	■	■	■								
4	Submission of Progress Report 2									●						
5	Seminar										■	■	■			
6	Project Work Continue									■	■	■	■			
7	Poster Exhibition											●				
8	Submission of Dissertation (Soft bound)													●		
9	Oral Presentation														●	
10	Submission of Project Dissertation (Hard Bound)															●

● Project milestone
■ Process

APPENDIX IV: PROJECT GANTT CHART

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Building the Receiver Part	■	■	■	■											
2	Test the prototype	■	■	■	■											
3	Submission of Progress Report 1				●											
4	Seminar 1					■	■									
5	Building the Transmitter Part	■	■	■	■	■	■	■								
6	Test the transmitter	■	■	■	■	■	■	■								
7	Test the overall prototype	■	■	■	■	■	■	■		■						
8	Submission of Progress Report 2									●						
9	Seminar										■					
10	Finalizing project prototype									■	■		■	■		
11	Poster Exhibition											●				
12	Submission of Dissertation (First Draft)												●			
13	Submission of Dissertation (Soft Bound)													●		
14	Oral Presentation														●	
15	Submission of Dissertation (Hard Bound)															●

● Milestone

■ Process

APPENDIX V: ANTENNA & RESONATOR

1. ANTENNA

The shapes and sizes of the antenna will depend on the frequency that the antenna is trying to receive. The antenna can be a long, stiff wire to something like a satellite dish. The size of an optimum radio antenna is related to the frequency of the signal that the antenna is trying to transmit or receive. The reason for this relationship has to do with the speed of light, and the distance electrons can travel as a result.

In one cycle of the sine wave, the transmitter is going to move electrons in the antenna in one direction, switch and pull them back, switch and push them out and switch and move them back again. In other words, the electrons will change direction four times during one cycle of the sine wave.

For example, a radio station is transmitting a sine wave with a frequency of 680,000 hertz. That means every cycle completes in (1/680,000) 0.00000147 seconds. One quarter of that is 0.0000003675 seconds. At the speed of light, electrons can travel 0.0684 miles (0.11 km) in 0.0000003675 seconds. This means the optimal antenna size for the transmitter at 680,000 hertz is about 361 feet (110 meters). For a higher frequency, the time will be shorter, thus resulting in shorter antenna length.

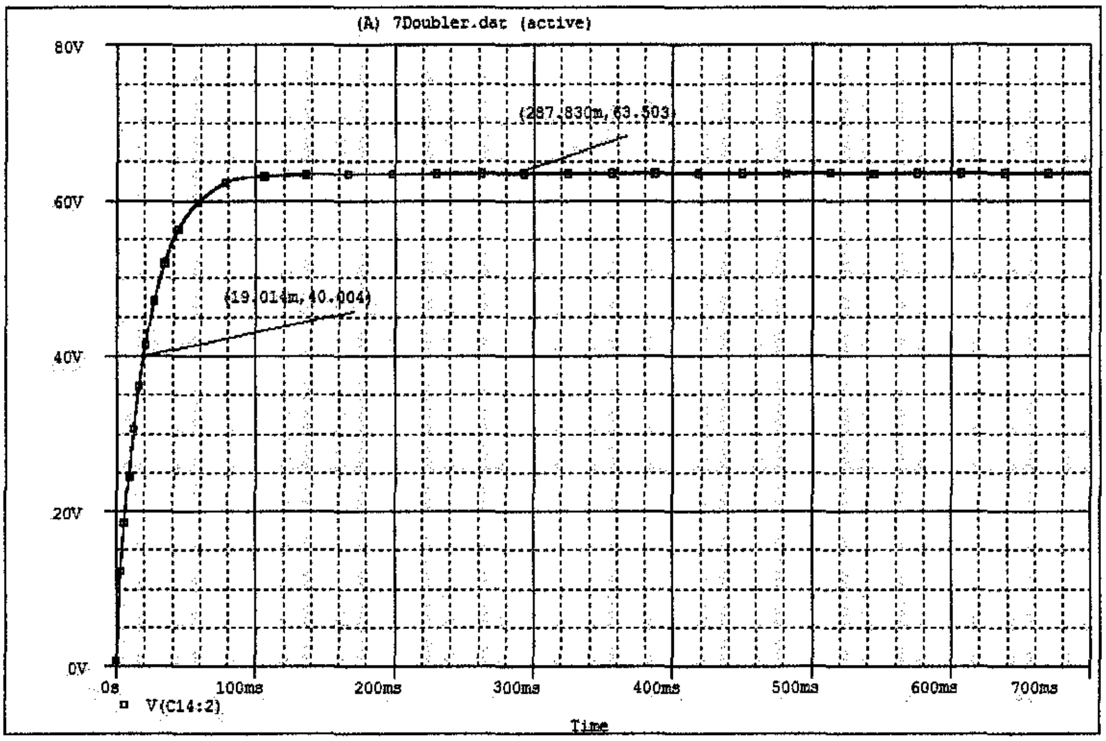
2. RESONATOR

In a simple radio, a capacitor/inductor oscillator acts as the tuner for the radio. Thousands of sine waves from different radio stations hit the antenna. The capacitor and inductor resonate at one particular frequency. The sine wave that matches that particular frequency will get amplified by the resonator, and all other frequencies will be ignored.

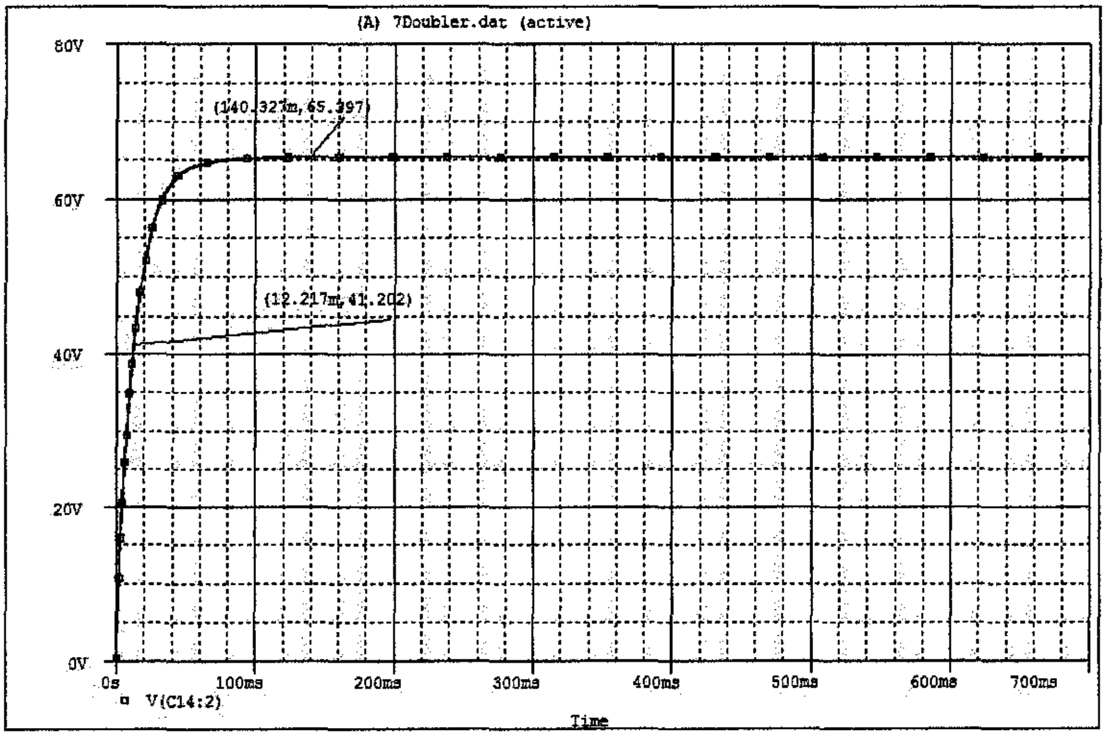
In a radio, either the capacitor or the inductor in the resonator is adjustable. Varying the capacitor changes the resonant frequency of the resonator and therefore changes the frequency of the sine wave that the resonator amplifies. It is the same if the inductor is varied. From this, it can be concluded that the value of both capacitor and inductor have an effect in determining the resonant frequency.

APPENDIX VI: SIMULATION RESULTS

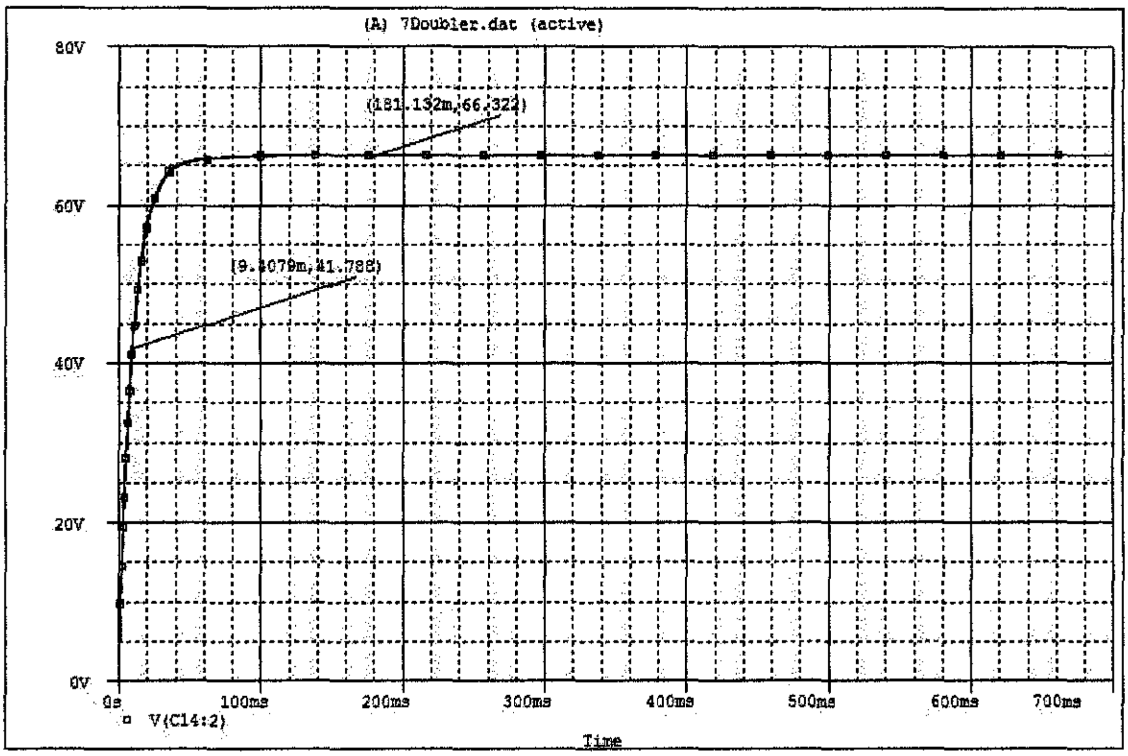
Test 2: Stage capacitor (different value)



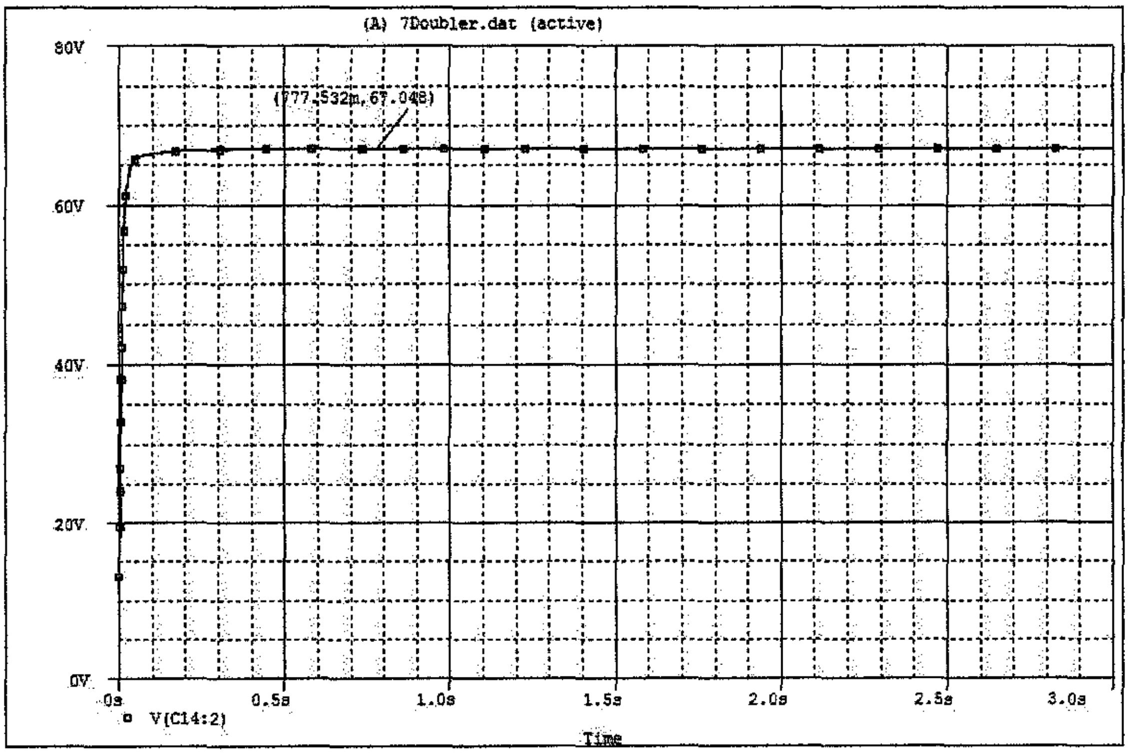
Graph 1: Capacitor value = 1 nF



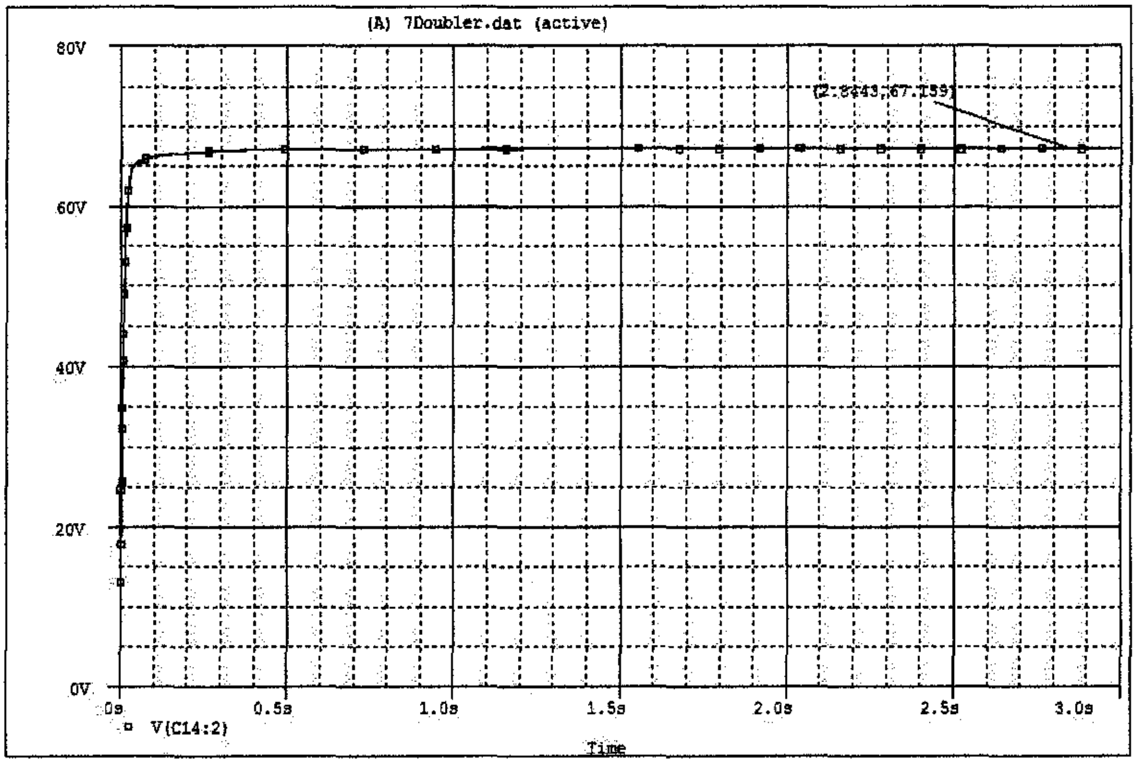
Graph 2: Capacitor value = 2.2 nF



Graph 3: Capacitor value = 4.7 nF



Graph 4: Capacitor value = 22 nF



Graph 5: Capacitor value = 47 nF