# Modelling and Performance Analysis of Power Efficient RF Energy Harvesting System

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Under The Guidance of


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# CERTIFICATE

This is to certify that the dissertation entitled "**Modelling and Performance Analysis of Power Efficient RF Energy Harvesting System**" submitted by Aeiswarja Biswas (Examination Roll No: M6VLS23010; University Registration No: 154120 of 2020-2021) of Jadavpur University, Kolkata, is a record of bonafide research work under my supervision and be accepted in partial fulfilment of the requirement for the degree of MASTER OF VLSI DESIGN AND MICROELECTRONICS TECHNOLOGY of the institute. The research results represented in this thesis are not included in any other paper submitted for the award of any degree to any other university or institute.

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# DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC THESIS

I hereby declare that this thesis titled "**Modelling and Performance Analysis of Power Efficient RF Energy Harvesting System**" is an original research work done by me under the guidance of my supervisor. This work has not been submitted previously to any other institute.

All the information has been obtained and presented in accordance with Academic rules and Ethical Code of Conduct of the institute.

I also declare that, as required by the rules and conduct, I have cited and referenced the materials that are not original to this work.

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# ABSTRACT

*The use of Radio frequency (RF) Energy Harvesting System (EHS) has been increased day by day as it can harvest the ambient RF energy. It refers to an energy conversion technique which converts the electromagnetic energy to Direct Current (DC) energy. With the advancement of the communication systems and VLSI technology, RF EH has been emerged as an upcoming area in the recent past. Though other nonconventional energy sources such as, solar, wind, tidal etc. are already in race, RF EHS can also be considered as a good alternative of battery having immense potential to come up as an environmental friendly solution. The main reason of selecting this topic is the abundance of RF energy in the surrounding medium. Also, RF EHS can reduce the wastage of battery and increase the lifespan. Though few works have been carried out in this area, there is enough scope to explore this domain of work in the near future.*

*The above background has motivated to designing an RF EHS with the requirement of low power as well as low area which could be successfully used in various applications. In VLSI domain use of small chips are increasing day by day. The prime objective of the present research work is to propose RF EHS improved performance in terms of dc output voltage, output power, power consumption and time delay. In order to achieve this, NMOS based Schottky diode and PMOS based Schottky diode models will be proposed for the design of the RF EHS. Moreover, other design modules such as, p-n junction model file, half wave rectifier model file etc. will also be incorporated in the design process to compare the performance of the proposed design with the existing designs. The design*

*of RF EHS has been done by RF sources, matching circuit, transformer, rectifier and filter. The design has been carried out using T-SPICE simulator. The design of the proposed model of RF EHS has been carried out using Schottky diode, where it is developed using MOS technology, both NMOS and PMOS. The design has also been developed using p-n junction diode model and half wave rectifier model for the purpose of comparison. The performance of RF EHS is analyzed through a number of parameters such as, output dc voltage, output power, power consumption and time delay.*

# CHAPTER 1

# INTRODUCTION

## 1.1. Background

Radio Frequency (RF) Energy Harvesting System (EHS) refers to an energy conversion technique which converts the electromagnetic energy to Direct Current (DC) energy. With the advancement of the communication systems and VLSI technology, RF EH has been emerged as an upcoming area in the recent past. Though other nonconventional energy sources such as, solar, wind, tidal etc. are already in race, RF EHS can also be considered as a good alternative of battery having immense potential to come up as an environmental friendly solution.

## 1.2. Motivation

The above background demanded for intensive research of designing RF EHS, involving low power and low area. The main reason of selecting this topic is the abundance of RF energy in the surrounding medium. For example, ambient RF energy can be harvested from a variety of source like, mobile towers, satellite stations, radio station, multi media broadcasting, wireless internet etc. Also, RF EHS can reduce the wastage of battery and increase the lifespan. In other words, it can control pollution. Though few works have been carried out in this area, there is enough scope to explore this domain of work in the near future. This has motivated to designing an RF EHS with the requirement of low power as well as low area which could be successfully used in various applications.

## 1.3. Objective

The main objective of this thesis work is to develop an RF EHS with lesser power as well as area requirement using T-Spice simulator. In order to achieve this, NMOS based Schottky diode and PMOS based Schottky diode models will be proposed for the design of the RF EHS. Moreover, other design modules such as, p-n junction model file, half wave rectifier model file etc. will also be incorporated in the design process to compare the performance of the proposed design with the existing designs. The performance of RF EHS is measured with a number of parameters such as, dc output voltage, output power, power consumption, delay time etc.

## 1.4. Methodology

In this research work, the design of RF EHS is modified by various diode models. Low power design technique has been attempted in this work. The design has been attempted with NMOS and PMOS based Schottky diodes and compared with the other existing designs in terms of output dc voltage, power consumption time delay. This proposed architecture is implemented using T-Spice software (S-Edit Win64 16.30.20150626.04:37:24). In addition, the performance analysis of RF EHS is carried out using T-Spice and using W-Edit to produce the output waveform.

## 1.5. Contribution

The design of power efficient RF EHS is proposed in this thesis. The following are the major contributions to this work:

- ❖ A novel RF EHS has been designed by RF sources, matching circuit, transformer, rectifier and filter. The design has been carried out using T-SPICE simulator.
- ❖ The design of the above proposed model of RF EHS has been carried out using Schottky diode, where it is developed using MOS technology, both NMOS and PMOS.
- ❖ The design has also been developed using p-n junction diode model and half wave rectifier model for the purpose of comparison.
- ❖ The performance of RF EHS is analyzed through a number of parameters such as, output dc voltage, output power, power consumption and time delay.

## 1.6. Outline of Thesis

The organization of this thesis is as follows:

- ➢ Chapter 2 explains the detailed literature review of the design of proposed work.
- ➢ Chapter 3 discusses the proposed design along with the existing work.
- ➢ Chapter 4 summarizes the simulation results of the proposed work and its comparison with the existing work.
- ➢ Chapter 5 concludes this thesis work. Some other related works which can be developed in future have also been mentioned here.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. Overview

This chapter provides a detailed survey of the literature based on designing of RF EHS. With the advancement of technology, many researchers have carried out works on the designing of RF EHS. This chapter presents the review and analysis of the background work related to this thesis.

## 2.2. Review of the Related Work

The use of RF source [1] came from preserving earth's ecological balance. The logging of trees, forest fires etc are the main causes of deforestation. Large-scale deforestation and RF source alters the climate, contributing to global warming, drought, and other different adverse effects. Because of these negative effects, forest management departments and source of RF energy have implemented measures to monitor the environment and stop destruction. For monitoring and prevention, a number of surveillance techniques have been used. This knowledge will help to increase the ground based sensing technique and remote sensing technique. The process of implementation of RF source has not been mentioned in this work.

The design factors for an RF energy harvesting integration strategy have been discussed in [2]. The plan contains a rectifier that generates DC voltage and a resonant voltage boosting network that creates high amplitude swing. In this method, a resonant tank is employed to produce the necessary voltage swing to drive the next step of the rectifier. Radio frequency power is transformed into direct current energy by the rectifier and then it stored charge in the capacitors. The proposed plan seems to be a viable option for long-distance self-power wireless application based on the simulation findings.

Work described in [3] presents a method and related circuitry for obtaining electromagnetic waves in the RF or microwave part of the spectrum with a range of incident power densities in the range of tens of muW with close to maximum output power. Open loop resistor simulation at the input port of a power converter is used to show that the peak power point of a low-power rectifying antenna source may be tracked over a broad range of incident RF power densities. The boost converter is shown with a straightforward low-power control strategy for resistor emulation. The outcomes show that energy harvesting with changeable low-power radiative RF sources can be accomplished simply and practically by simulating resistors.

A new approach of designing rectifying antenna (rectenna) circuits is described in [4]. The succeeding sources theory, which is often applied to power electronics conversion, is introduced and integrated. The proposed circuit simulation relies on dimensioning of good filter and is sufficient for the design of rectenna. Here, localised elements technology is used to create the circuits as opposed to the more common micro strip lines technology. Measurement findings are also used to demonstrate and validate the simulation results.

RF energy harvesting offers a bright future for producing a few quantity of electrical power to connect circuits that has been described in [5]. The overview and developments in the region of radio frequency energy harvesting are also presented in [5]. A modified version of an existing CMOS-based voltage doubler circuit is provided to produce a 160% increase in output power over traditional circuits at 0dBm input power. The performance of an RF-EH circuit based on Schottky diode is also examined from simulations and real-world testing.

RF-EH design difficulties can be generically categorised into operational bandwidth (BW), compactness, form factor, and radio frequency to direct current (RF-to-DC) and power conversion efficiency (PCE). A comprehensive review of the key elements of an RF-EH system is presented in [6]. Compact RF-EH circuits have been realised using a variety of design strategies, greatly advancing the design of millimetre wave antennas. Additionally, practical methods for configuring the RF-EH system's antenna modules based on the suggested spectrums have also been described. In this study, design trade-offs are viewed from a conceptual perspective together with insightful EH solution approaches for wireless power communications.

Power management technology for energy harvesting [7] presents a significant challenge for energy storage and management because the delivered voltage is frequently inappropriate for standard power management chips because it is much lower than the threshold voltage of standard electronic devices under very low indoor light intensity. This study provides a unique ultra-low start-up voltage power management circuit. It can boost input voltage as low as 40mV to produce output voltage (4.1V) for a wireless humidity sensor node. When the signal from the humidity sensor node is transmitted, the measured prototype can successfully drive the wireless sensor load.

The Digital TV (DTV) band micro-power RF-EH design architecture is provided in [8]. Also a boost converter circuit and a rectenna circuit are presented here. If a 550 MHz single tone excitation is used, the conversion efficiency of the rectifying antenna (rectenna) is measured to be 0.4% for a -40dBm input and 18.2% for a -20dBm input respectively. For use with this antenna, a boost converter circuit is designed and constructed. By simulation and measurement, it has been shown that the proposed boost converter can increase voltages as low as 400mV DC, which is sufficient for battery and capacitor recharging. However, this is predicated on the assumption for starting the boost converter circuit and the battery or capacitor of that circuit has some initial charge or energy. The antenna circuit has the ability to rectify up to 0.46V DC in given simulation.

RF energy harvesting systems produce a little amount of electrical power, but depending on the methodology, it is capable for low power consumption devices [9]. As a result, it is feasible to prolong battery life while lowering environmental pollutants. For low power mobile devices, this work provides a rectenna with a 4x4 patch antenna operating at 2.13 GHz. According to the assessed RF-EHS results, low power mobile devices can function at a distance of 12 metres.

The work presented in [10] describes an energy conversion module for 900 MHz band RF-EHS, where an attempt has been made to optimize the voltage doubler stages. In order to power the low power devices and circuits, the energy conversion module converts Radio Frequency (RF) impulses into Direct Current (DC) voltage at the specified frequency band.

The design is developed on the basis of the Villard voltage doubler circuit. In this study [10], a seven stage Schottky diode voltage doubler circuit is designed, modified, simulated, fabricated, and tested. For the modelling and simulation work, Multisim was employed. At the designated frequency band, simulation and measurement were done for various input power levels. The circuit can generate 3mV across a 100k load for an equivalent incident signal of -40dBm. The findings also demonstrate a multiplication factor of 22 at 0dBm, which leads in a measured DC output voltage of 5.0V. Eventually, this voltage may take the place of batteries in sensor networks to power low power sensors.

The study in [11] examined the available techniques for RF-EH and introduces components for enhanced collection circuit that may be incorporated into any low power electronic device with requirements. A microstrip patch antenna with an impedance matching network provides an additional option for increased energy collecting rates, which leads to a faster accumulation of charges. The design of a rectenna circuit, which comprising a microstrip patch antenna and a rectification section with seven components, continues to be the core contribution of this research project. The efficiency of power conversion needs to be raised in order to deliver a workable solution that is efficient enough for market adoption in low power mobile devices.

Radio frequency (RF) energy can be obtained from either specialised sources or the surroundings in [12]. The three essential components of a traditional RF harvester are an antenna, a matching network, and a rectifier. A half-wave rectifier with a single zero-bias Schottky diode (HSMS2850) was chosen as a rectifier in this paper. A theoretical analysis was done first, then simulations using advanced design system (Harmonic Balance) were run. When utilising the diode rectifier's actual model instead of ideal components, simulations reveal efficiencies of 75% for a 10dBm input power. The design is carried out in PCB.

This paper [13] propose a novel rectifier design for RF energy harvesting from ultra-low sources, such as ambient RF sources, which are typically in the range of a few to few tens of uW. If the rectenna is connected directly to its actual load under these circumstances, unsatisfactory results may follow because either the minimum power or the minimum activation voltage may not be concurrently available. For this reason, a double-branch rectifier topology rather than the conventional single-branch is being investigated for the power management unit (PMU). In comparison to the conventional arrangement, the new PMU, placed between the rectenna and application circuits, enables the system to function with a substantially lower input power while maintaining efficiency during steady-state power conversion.

This paper [14] provides an overview of the fundamentals and specifications for radio-frequency (RF) energy harvesting or transmission-based powering of wireless sensors. We conclude that RF energy delivery is superior for powering small-sized sensors after the viability of harvesting is discussed. This discussion leads to the conclusion that indoor line-of-sight conditions are capable of achieving an attenuation that is superior to open space. The rectifier, dc-dc boost converter, antenna and the components of the rectifying antenna (rectenna) are also discussed. All of these rectenna subcomponent's power efficiencies are examined, and then a few examples are provided. Several safety measures must be implemented in order to RF energy transport to be a workable powering solution for low-power sensors. The parameters of the propagation channel must be taken into consideration when designing the transmit antenna radiation pattern. The power transfer efficiency of the rectifier and the boost converter need to be maximised, and all of the antenna's subcomponents need to be impedance matched.

Although RF harvesting circuits have been tested for more than 50 years, only few of them have been successful in obtaining energy from unrestricted ambient (i.e. non-dedicated) RF sources. Motivated by this, an RF energy harvester has been implemented compatible to ambient RF power levels available in both semi-urban and urban areas. A city-wide RF spectral scan was conducted from outside all 270 London Underground stations at street level to examine the possibility for ambient RF energy harvesting. Based on the findings of this study, four harvesters were created to cover four frequency bands from the biggest RF contributors (DTV, GSM900, GSM1800, and 3G) within the ultrahigh frequency (0.3-3 GHz) region of the frequency spectrum. These harvesters consist of an antenna, impedance-matching network, rectifier, maximum power point tracking interface, and storage element. For each band, prototypes were created and constructed. Our initial GSM900 prototype yielded a 40% efficiency when the prototypes overall end-to-end efficiency was assessed using genuine input RF power sources. Using four prototypes, we discovered that about half of the London Underground stations are good places for collecting ambient RF energy. Additionally, multiband array architectures were created in order to offer additional operational freedom. When all the ambient RF energy harvesters and alternative energy harvesting technologies were compared in terms of output dc power density, it was discovered for the first time that ambient RF harvesting could be competitive with the other technologies.

This work [16] presents the design of a two short stubs-based high impedance transmission line with 10mW concurrent triband radio frequency rectifier operating at 1050, 2050, and 2600MHz. According to experimental findings, the efficiency is attained at 1050 MHz at 59.2%, 2050 MHz at 35.6%, and 2600 MHz at 52.2%. The suggested triband rectifier has the capacity to capture radio frequency energy from the corresponding operational frequency sources, which makes it superior to the state-of-the-art multi-band rectifiers in this regard. TriBand, RF, Wireless energy harvesting (WEH), and Rectifier are the terms used in the index.

The use of gadgets like RFID and Zigbee is constrained by the fact that they are fueled by transportable energy sources, like batteries. This study [17] created RF energy harvesting with W-CDMA for a low power RF device to help alleviate this issue. Because the diode threshold is greater than the rectifying antenna's (rectenna's) received peak voltage, diodes with low turn-on voltage are necessary. Consequently, an HSMS-286 schottky diode was employed. For the W-CDMA signal, a prototype of an RF energy harvesting device displayed a maximum gain of 5.8dBi. Using a PTFT board with 10 dielectric constants, 16 patch antennas were produced. The transmitter in low power RF devices needs a step-up voltage of 2.5–5V with a maximum current of 35mA. The Texas Instruments TPS61220 was employed as a low input voltage step-up converter to fulfil this need. Based on the results of the evaluation, a rectenna may operate Zigbee at a distance of 12 metres with an achievable incident power of 926 mV.

This research [18] focuses on a rectifying antenna (rectenna) based wireless energy harvesting system. A wideband cross-dipole antenna, a microwave low-pass filter, and a doubling rectifying circuit using Schottky diodes as rectifying elements make up the suggested device. A few wideband antennas were previously studied between 1.7 and 2.5 GHz. The innovative wideband rectenna design that can capture ambient radio frequency (RF) power at frequencies ranging from 1.7 to 2.5GHz, which makes this study unique. In this technology, a brand-new wideband cross dipole is created and employed to accomplish the needed duel polarisation and bandwidth. Additionally, the voltage doubling rectifying circuit is enhanced to provide the highest performance at urban power density levels less than 200 $uW/cm^2$. The suggested rectenna's properties over the intended frequency range are examined, and an integrated rectenna is simulated, constructed, and tested for low input power densities ranging from 5 to 200 $uW/cm^2$. A good agreement is reached when the rectenna's simulation and measurement findings are compared. The findings show that, the greatest rectenna conversion efficiency is close to 57% at 1.7GHz and more than 20% over the wideband of interest for incident power density of 120 $uW/cm^2$. One of the primary elements influencing the efficiency of the rectenna's energy conversion is stated to be impedance matching. The GSM/3G/4G and ISM 2.4 GHz bands provide considerable promise for this innovative wideband antenna to capture wireless energy.

The different design restrictions for radio frequency energy harvesting circuits are the main subject of [19]. Matching networks like the Π-type and L-type are used to examine the effectiveness of RF-EH circuits. According to the simulation results, the harvesting circuit produces a higher output voltage when a high-Q value matching network is used. This circuit, however, seems to be more susceptible to changes in input frequency and quantities of lumped elements. Under various load circumstances with lumped element values, a theoretical examination of matching efficiency and voltage gain is discussed. According to this research, the circuit that delivers the voltage gain and best matching efficiency is one that has high load impedance and low internal resistance components. In order to achieve a greater output voltage, it has been discovered that high saturation current, low series resistance, etc. are required. Also low junction capacitance values of the diode are crucial here.

In order to act as a guide for the design of RF-EH devices, [20] offers a summarized part of radio frequency power harvesting technology. Energy harvesting circuits are designed to operate with low voltages and currents. Also it depends on cutting-edge electrical technology to achieve great efficiency. As a result, thorough evaluations and discussions of different designs and their exchanges are provided. Finally, RF power harvesting applications are described.

In this article [21], we provide the outcomes of simulations performed on three piezoelectric materials such as Zinc Oxide, Lead Zirconate Titanate (PZT-2), and Quartz with the aim of generating RF functionality and converting the mechanical energy to electrical energy. The analysis of fatigue in cantilevers made of each of these materials independently is included in the scope of this paper. The beams and piezoelectric materials were simulated and examined using multiphysics simulation software. The effectiveness of these materials at various frequencies was investigated. The findings of our work provide an opportunity to assess the possibility of employing piezoelectric materials in RF MEMS devices to minimize power consumption.

The architecture of an Ultra Low Power (ULP) Micro Energy Harvester (MEH) employing an RF signal as an input is shown in [22]. RF provides a number of advantages over other ambient sources because it is not impacted by changes in weather or time, doesn't require exposure to heat or wind, and may be relocated arbitrarily within the range of the transmission source. Impedance matching must be taken into account as the most crucial component when RF is the only input in order for the antenna to transfer the greatest power. Some energy harvesters use ‘conjugate matching network’ as the potential solution. The problem with this approach is that it must simultaneously take into account the conjugate matching network and voltage boosting. We suggest a ULP Radio Frequency Micro Energy Harvester (RFMEH) to address this issue. This device will use a control loop to maximize power transfer while minimizing power reflection. The system's sensitivity and RF to DC conversion efficiency will both be increased by the suggested architecture. This is accomplished by employing an effective rectification technique to convert RF to DC, a DC-DC boost converter to enhance the dc output voltage, an adaptive control circuit to change the boost converter's switching timing, and the optimum output voltage-producing voltage limiter and regulator. Before implementing the design in MOS 0.13m technology, the proposed ‘ULP RFMEH’ architecture needs proper planning and simulation using PSPICE software, Verilog coding using Mentor Graphics, and functional verification using FPGA board (FPGA). With an efficiency of more than 60%, the suggested architecture will provide an output voltage of about 2.45V from a low input power level (-20dBm). In comparison to earlier designs, this one will consume less power, and it can be used to power microbiological applications or healthcare monitoring systems.

In this study [23], the rectifier module for an RF energy harvesting system operating in the 915MHz range is optimised. This module transforms the RF signal in the specified frequency band into direct-current voltage to ultra-low power bio-medical sensors. To study the effectiveness and sensitivity of various types of rectifier circuits, transient analysis is used. The voltage boosting network raises the voltage at the full wave rectifier’s input in order to increase power conversion efficiency. The system's optimal parameters, such as the load value, capacitance value, and inductance value are determined on the assumption that the system is in resonance. According to the results of the simulation, a circuit based on passive components can greatly raise the RF input voltage and expand the rectifier's input range. At the same amount of input, the improved circuit increases output voltage by about 400mV over the output voltage of the existing full wave rectifier. As a result, the input range that can be converted to dc output will be expanded.

The work presented in [24] describes about Ferrite rod antenna which is mainly used in hi-fi tuners as well as portable transistor broadcast receivers. The industry is declining as VHF FM and digital services become more prevalent. The use of ferrite rod antennas in wireless applications, such as RFID, is growing, nevertheless. Here, a significant number of antennas are needed.

For the purpose of developing a system based on RF energy harvesting employing a novel receiving antenna design, in this study [25] we concentrate on ambient radio frequency energy provided by commercial broadcasting stations. As the antenna features can influence the quantity of energy gathered, a variety of antenna designs have been proposed for use in RF energy harvesting systems. A suitable receiving antenna design is therefore crucial. With the suggested antenna, energy harvesting efficiency over the 2.45 GHz and 5 GHz Wi-Fi bands will be significantly increased. In severe conditions or isolated locations where other energy sources are impractical, this offers a possible alternative energy source for powering sensors. On the same circuit board, the dual-band antenna and RF energy harvesting system are simply integrable. To assess antenna performance and look into the impact of various design parameters on performance, simulations and experiments were done. The receiving antenna delivers peak gain of more than 4dBi over the operational band and complies with the necessary bandwidth standard.

This work [26] describes the design, optimisation, and testing of rectenna circuits on transparent substrates that are intended for wireless power harvesting and operate in the GSM, UMTS, and Wi-Fi frequency bands. The proposed circuits exhibit greater than 95% transparency and are engraved on 1.7mm thick optically clear plexiglas. Each circuit has a coplanar stripline RF to DC rectifier based on a shunt SMS7630 Schottky diode and a linearly polarised circular loop antenna. The prototypes provide output DC voltages of about 300, 200, 100, and 100mV at 940, 1860, 2140, and 2490 MHz, respectively, for 1 uW/cm$^2$ (E = 1.94V/m) power density. Overall efficiencies of 50, 30, 30 and 25% were attained at the same frequencies for the same power density.

The design of RF EHS based on Schottky diode model file is simulated by LT-Spice in [27]. This work is used amplitude modulated signal as a source. It has ferrite core receiving antenna which is used in matching circuit. The transformer and the rectified output have shown dc output voltage. Simulation results also have shown the proposed model efficiency versus load resistance. This knowledge will help to design the system using other software to increase efficiency.

A Field Programmable Gate Array (FPGA) based evaluation platform for EH Embedded Systems (EHES) is described in [28]. Extremely low power embedded systems are crucial for smart cities and the IOT since they are in charge of collecting, processing, and transmitting critical environmental data. Even for battery replacement, some of these systems ought to function for a very long time without any human involvement. By turning ambient energy sources into electrical energy, EH technologies enable embedded systems to be fuelled from the environment. However, the nature of the sources of energy, which are typically unpredictable and uncontrollable, has a significant impact on energy-harvesting embedded systems (EHES). This paper also suggests simulating the I-V curves of low power EH transducers to upgrade the analysis of energy management strategies in energy harvesting embedded system. The emulation of energy source is managed by an FPGA based platform with an integrated logic analyzer, allowing real time data collection from the energy harvesting embedded system in various consideration scenarios.

The study [29] discusses how energy harvesting devices are becoming more popular as a result of rapid advancements in numerous new developing technologies in electronics and telecommunication. The antenna, impedance matching, and rectifier components of the receiver are the subject of the research. The rectenna is used in radio frequency (RF) energy harvesters as part of the Micro Electromechanical System (MEMS) technological design. MEMS is a miniaturisation technology that has primarily been adapted from the integrated circuit industry and is used for systems other than electrical ones. Because RF can be broadcast by many wireless systems in unlicensed frequency ranges, it is prioritised over other ambient sources. It needs improvement and increased Direct Current (DC) voltage generated by RF energy harvesters because the amount of energy extracted from the ambient RF is so low. A dual band MEMS rectenna is suggested for this reason in order to maximize efficiency. The 'Power Management Unit' (PMU) is placed between the MEMS rectenna and the load. To achieve the best output voltage, the system has a voltage regulator and temporary energy storage. The system that is suggested in the study was created using Mentor Graphic modelling software and PSpice for design and simulation. The claimed outcome of the RF MEMS energy harvester is to offer functional conversion efficiency and dependable energy harvesting system to reach 1.5-3.0 V output voltage for operating frequency at 1.9 and 2.45 GHz from RF input power at -20dBm with reveal about 100% improvement over other existing designs. The proposed design may serve as the foundation for future technological innovations that enable wireless transmission powered solely by RF MEMS energy harvesters.

## 2.3. Outcome of the Review

A survey of the literature on design and simulation of RF EHS was presented in this chapter. Efficiency of circuit performance has been identified as important attribute of design in VLSI technology based on the preceding review. A general overview of designing RF energy harvesting system using different technologies has been provided along with a detailed discussion. Though many works have been carried out in this domain, many more works are yet to come in future as there is always huge scope of improvement in research. Based on this trend, Tanner EDA platform based design of efficient RF EHS has been proposed in this thesis which is presented in the subsequent chapter.

# CHAPTER 3

# PROPOSED WORK

## 3.1. Overview

RF Energy Harvesting System (EHS) is mainly preferred due to the availability of RF energy in the surrounding environment. We know that RF energy is generally harmful for us and for nature also. It is also very true that modern society cannot survive or progress without the intervention of the RF energy or RF sources. Hence this RF energy can be used fruitfully in an energy harvester which could be a good alternative of battery. So the effective design of an RF Energy harvesting System or RF Energy harvester could be used successfully for transmitting & processing information in a communication system.

This chapter mainly includes the efficient design of RF EHS using some of the available model files of Schottky diode in T-Spice. Moreover, similar system model has been devised using p-n junction diode. Furthermore, the design is modified with half-wave rectifier model. Finally, the design of RF EHS has been proposed by incorporating NMOS and PMOS based Schottky diodes.

## 3.2. Architecture of RF Energy Harvesting System

Electromagnetic energy is transformed into direct current voltage via an RF EHS [27].

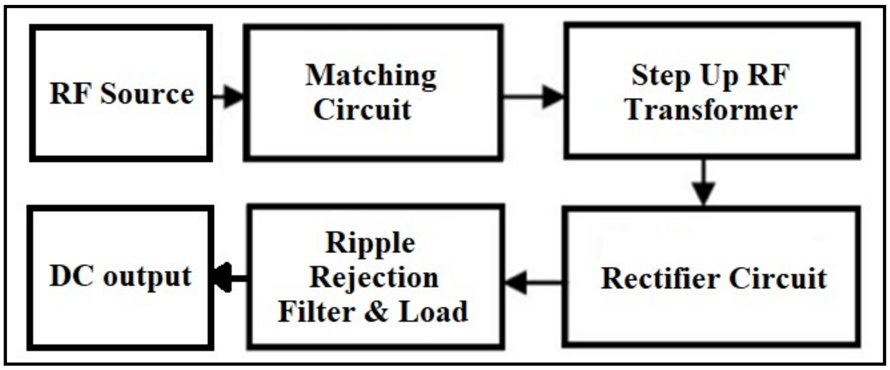



Fig 3.1: Block Diagram of RF Energy Harvesting System

The above figure [27] describes as the signal flows from antenna to the rectifier through the matching circuit and RF transformer. Antenna receives signal from RF source. Matching circuit is used for maximum power transfer. Step up transformer has been boost up signal voltage level through mutual inductance. Rectifier circuit rectified DC voltage with ripple rejection filter. Here, Filter is used for reducing ripple. After these whole processes, we will get rectified output.

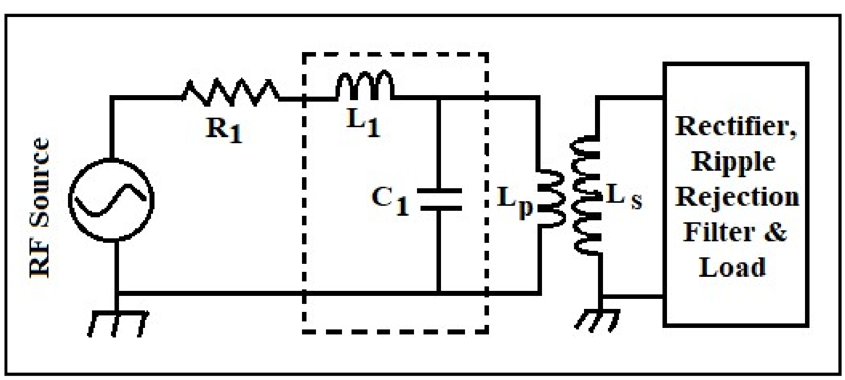



Fig 3.2: Simplified Circuit Diagram of RF Energy Harvesting System

In the above diagram, the RF source mainly comprises carrier signal amplitude modulated with a message signal. We added a resistance to reduce glitches. Practically we used this resistance. The matching circuit consists of the inductance and capacitance. The RF signal is connected to the half wave rectifier circuit through transformer coupling. The rectifier circuit also includes ripple rejection filter and load resistance.

### 3.2.1. Existing RF Energy Harvesting System using Schottky Diode

The existing RF Energy Harvesting System [27] has been reproduced using Schottky diode model file as shown below:

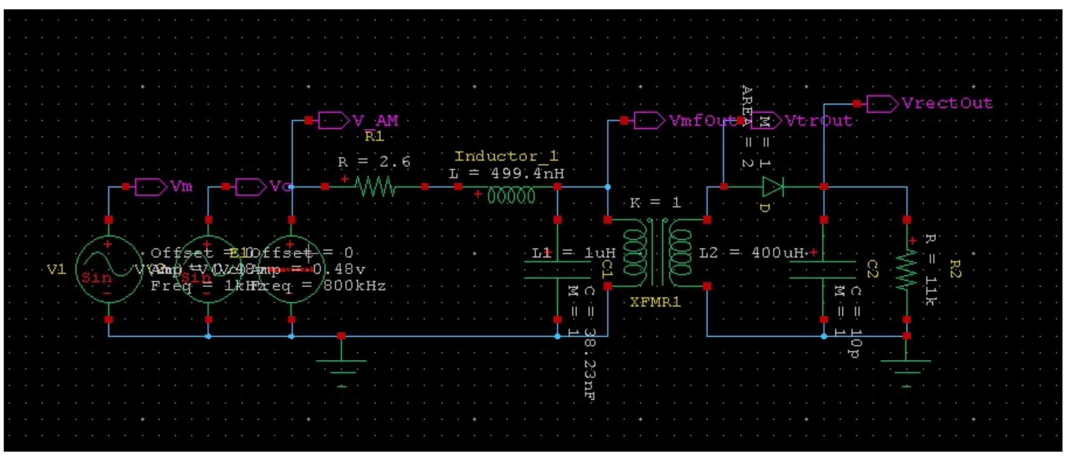



Fig 3.3: Schematic Design of RF Energy Harvesting System using Schottky Diode Model File

The schematic design of RF energy harvesting system in T-spice has been shown above. Here, two sinusoidal voltage sources and one behavioural voltage source are used for multiplying two sinusoidal voltage sources. Next, a resistance is used for reducing glitches. The inductor - capacitor combination acts as a matching circuit. This is followed by the rectifier circuit connected with a filter to reduce the effect of ripple. Six ports are also connected with two sinusoidal voltage source, behaviour voltage source, input of the transformer, output of the transformer and output of the rectifier.

Here, Schottky diode model file has been used which named as DI_SBMG0340L. This diode works in 40v and 30mA with saturation current of (IS) is13.9u. Here, ohmic resistance is taken as (RS) is 2.57 ohm, breakdown voltage (BV) is 40.0 volt, current at breakdown voltage (IBV) is10.0uA, zero bias bottom wall junction capacitance (per unit area) (CJO) is 2.65pF, multiplier factor to simulate multiple diode in parallel (M) is 0.333, Emission coefficient (N) is 2.82 and transit time (TT) is 1.44nsec.

## 3.2.2. Modified RF Energy Harvesting System

Design of RF EHS using different model files of diode are described as follows.

### 3.2.2.1. Modified RF Energy Harvesting System using P-N Junction Diode

RF energy harvesting system using p-n junction diode model file has been shown below:

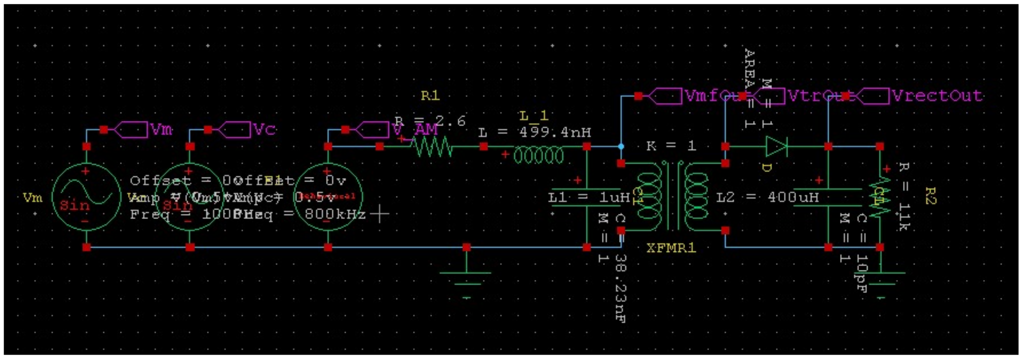



Fig 3.4: Schematic Design of RF Energy Harvesting System using P-N Junction Diode Model File

Here, p-n junction diode model file (1N4148W) is used. This diode works in saturation current (IS) of 10.4nA, ohmic resistance (RS) is 51.5mohm, breakdown voltage (BV) is 75.0 volt, current at breakdown voltage (IBV) is1.00uvolt, zero bias bottom wall junction capacitance (per unit area) (CJO) is 2.00pF, multiplier factor to simulate multiple diode in parallel (M) is 0.333, Emission coefficient (N) is 2.07 and transit time (TT) is 5.76nsec.

### 3.2.2.2. Modified RF Energy Harvesting System using Half Wave Rectifier Model

Following figure describes the design of RF EHS using half wave rectifier model file.

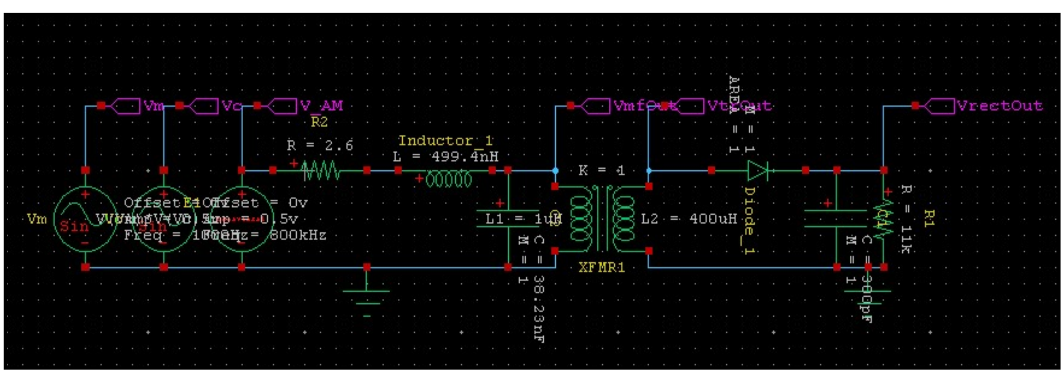



Fig 3.5: Schematic design of RF energy harvesting system using half wave rectifier model file

Here, half wave rectifier model file SBR130S3 is used. This diode works in 30v and 1A with saturation current (IS) of 7.30uA. Here, ohmic resistance (RS) is taken as 80.3mohm, breakdown voltage (BV) is 30.0 volt, current at breakdown voltage (IBV) is12.2uA, zero bias bottom wall junction capacitance (per unit area) (CJO) is 416pF, multiplier factor to simulate multiple diode in parallel (M) is 0.333, Emission coefficient (N) is 1.09, and transit time (TT) is 56.2nsec.

### 3.2.3. Proposed RF Energy Harvesting System

The design of RF EHS has been modified using MOS technology. The MOS based designs are described in the following sub-sections.

#### 3.2.3.1. Proposed RF Energy Harvesting System using NMOS Based Schottky Diode

The circuit diagram of NMOS based Schottky diode [30] is shown in Fig 3.6.

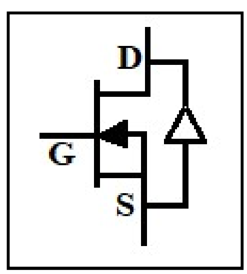



Fig 3.6: Design of Schottky Diode using NMOS

The above fig depicts a NMOS based Schottky diode where the body of the diode is made up of silicon. The MOS and diode together is called a device design. Diode is connected parallel to the channel of the device when body diode conducts. It mainly analyzes static and dynamic behaviour. For reverse recovery process, when diode turns off after conducting, the forward current and maximum blocking voltage have to be considered in reverse and forward bias respectively. The charge stored during the on state must be removed because the current does not reduce to zero immediately when diode goes from forward to reverse bias.

This model has been successfully incorporated in the proposed design and shown in Fig 3.7.

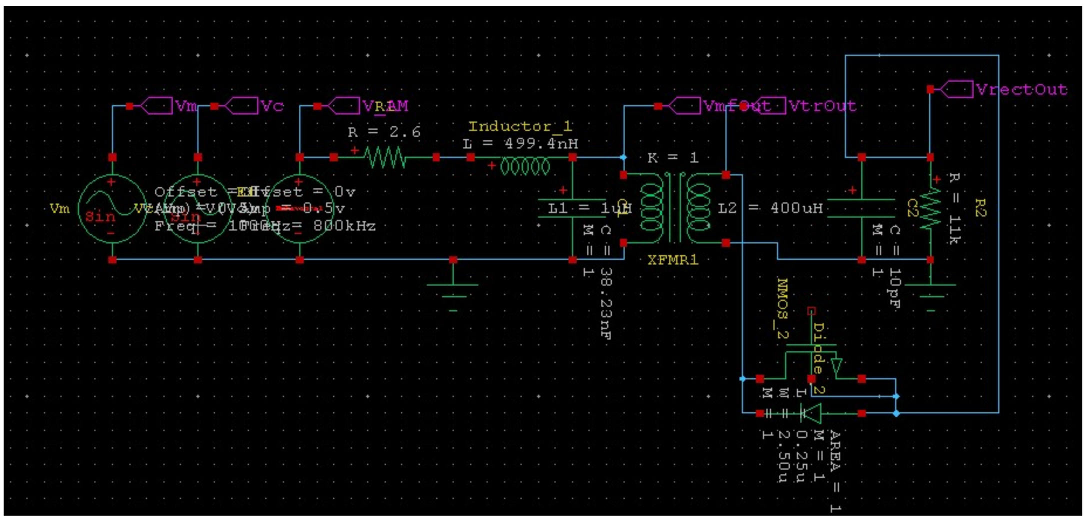



Fig 3.7: Schematic Design of RF Energy Harvesting System using NMOS Based Schottky Diode

For Schottky diode, we have used NMOS and p-n junction diode. The used specifications are: 1N4148W p-n junction model file and MOS version 3.1, level- 49 and threshold voltage- 0.36v.

### 3.2.3.2. Proposed RF Energy Harvesting System using PMOS Based Schottky Diode

The proposed model of PMOS based schottky diode is described in Fig 3.8.

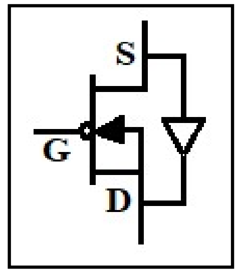



Fig 3.8: Design of Schottky Diode using PMOS

The above fig describes a schottky diode using PMOS which consists of a PMOS and a diode.

This model has successfully been used for the proposed design of PMOS based RF EHS as shown in Fig 3.9:

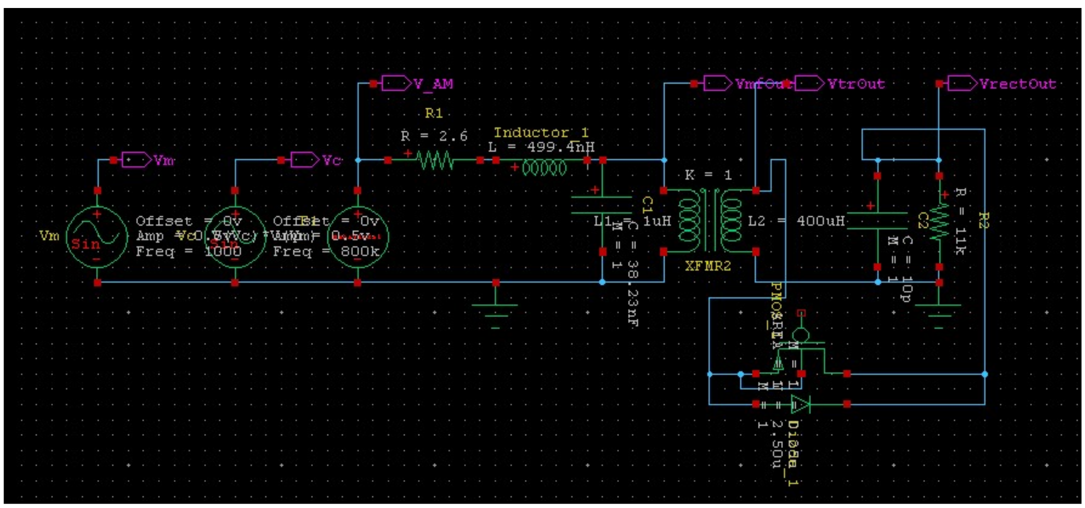
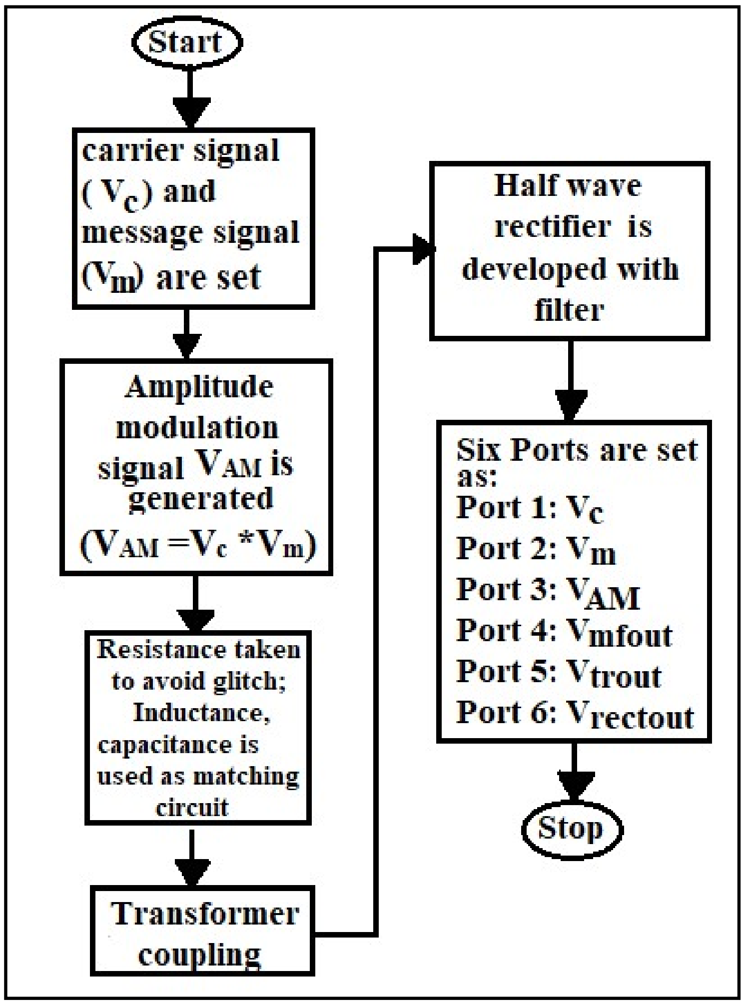



Fig 3.9: Schematic Design of RF Energy Harvesting System using PMOS Based Schottky Diode

For Schottky diode, PMOS and p-n junction diode are used. The description includes: p-n junction model file 1N4148W and MOS version 3.1, level- 49 and threshold voltage- 0.36v.

## 3.3. Work Flow of the Proposed Design

The flowchart of the RF Energy Harvesting System has been shown below:




$V_c$: Carrier signal voltage, $V_m$: Message signal voltage, $V_{AM}$: Amplitude modulation voltage, $V_{mfout}$: Matching circuit output voltage, $V_{trout}$: Transformer output voltage, $V_{rectout}$: Rectified output.

## 3.4. Discussion

Designing of RF energy harvesting system using some of the model files of Schottky diode, p-n junction diode and half wave rectifier have been described in this chapter. Moreover, the existing model of NMOS based Schottky diode is used for the effective design of RF EHS. Furthermore, PMOS based design of Schottky diode has been proposed and described. Finally, RF energy harvesting system using PMOS based Schottky diode is modelled and presented in this chapter.

# CHAPTER 4

# RESULTS AND ANALYSIS

## 4.1. Overview

This chapter presents the simulation of the proposed work. The design of RF EHS has been studied and compared with existing low cost RF EHS model. The proposed model has been simulated using T-Spice. The detailed analysis of performance of the proposed work based on MOS technology and existing low cost RF EHS has been presented below.

## 4.2. Simulation Environment

Tanner EDA has been used as simulation platform. Tanner EDA is comprising of S-Edit, T-spice, L-Edit and W-Edit. S-edit provides the schematic diagram of the design including voltages, currents, and noise parameters. T-spice is an editor where codes are written for the purpose of simulation. L-edit offers the layout of the design. In this work, L-edit has not been used. W-Edit is a waveform viewer that provides complex numerical data resulting from circuit simulation. In addition, W-Edit provides saved work spaces, scriptable graph construction etc.

Tanner EDA has the following specifications:

Tanner version: 16.30; Product Release ID: T-Spice Win64 16.30.20150626.02:41:53; Copyright © 1988-2015; graphic: Mentor Graphics Corporation; Scaling: 0.18um.

## 4.3. Setting of Parameters

Table 4.1: Parameters Used in Simulation

| | |
|---|---|
| Frequency of $V_c$ | 800KHz |
| Amplitude of $V_c$ | 0.5v |
| Offset of $V_c$ | 0 |
| Frequency of $V_m$ | 1kHz |
| Amplitude of $V_m$ | 0.5v |
| Offset of $V_m$ | 0 |
| Resistance ($R_1$) | 2.6ohm |
| Inductor (L) | 499.4nH |
| Capacitor ($C_1$) | 38.23nF |
| Primary inductance ($L_1$) | 1uH |
| Secondary inductance ($L_2$) | 400uH |
| Capacitor ($C_2$) for filtering | 10pF |
| Load resistance ($R_2$) | 11KOhm |
| In transient analysis, start time | 0ms |
| In transient analysis, stop time | 2ms |
| In transient analysis, maximum time step | 0.01us |

## 4.4. Simulation Results of Existing RF Energy Harvesting System using Schottky Diode

The simulation results of the existing RF energy harvesting system using Schottky diode have been presented here. The screenshot of T-Spice code corresponding to this design has been shown below.

```
********* Simulation Settings - General Section *********
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\schottky_diode(40v,30mA).md"

***** Top Level *****
CC1 VmfOut Gnd  38.23n $ $x=1500 $y=-100 $w=400 $h=600 $r=90
CC2 VrectOut Gnd  10p $ $x=3100 $y=-100 $w=400 $h=600 $r=90
RR1 V_AM N_1  R=2.6 $ $x=400 $y=415 $w=600 $h=150
RR2 VrectOut Gnd  R=11k $ $x=3615 $y=-100 $w=150 $h=600 $r=90
LInductor_1 N_1 VmfOut  L=499.4n $ $x=1200 $y=350 $w=600 $h=100
DD VtrOut VrectOut DI_SBMG0340L AREA=2 $ $x=2800 $y=400 $w=600 $h=120 $r=270
LPXFMR1 VmfOut Gnd 1uH
LSXFMR1 VtrOut Gnd 400uH
KXFMR1 LPXFMR1 LSXFMR1 1 $ $x=2100 $y=5 $w=600 $h=410
VV1 Vm Gnd  SIN(0 500m 1k 0 0 0) $ $x=-1200 $y=-100 $w=400 $h=600
VV2 Vc Gnd  SIN(0 500m 800k 0 0 0) $ $x=-600 $y=-100 $w=400 $h=600
EE1 V_AM Gnd  VOL='V(Vm)*V(Vc)' $ $x=-100 $y=-100 $w=400 $h=600

********* Simulation Settings - Analysis Section *********
.tran 0.01u 2m start=0m
.print tran v(Vm) v(VmfOut) v(Vc) v(VtrOut) v(V_AM) v(VrectOut)
.print tran i(RR2)
.power RR2
.measure tran tdelay trig v(V_AM) val=.1 rise=1 targ v(VrectOut) val=.1 rise=1

********* Simulation Settings - Additional SPICE Commands *********

.end
```

Fig 4.1: Screenshot of T-Spice Code

The screenshot of post simulation design details has been presented below.

```
Input file:    withdiodeRFenergyharvester.sp
Progress:      Simulation completed

Total nodes:   13    Active devices:   1    Independent sources:  2
Total devices: 12    Passive devices:  8    Controlled sources:   1

T-Spice - Tanner SPICE
T-Spice - Tanner SPICE
Version 16.30
Network license
Product Release ID: T-Spice Win64 16.30.20150626.02:41:53
Copyright © 1988-2015 Mentor Graphics Corporation

   Parsing "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\RF_Harvester_design\withdiodeRFenergyharvester\withdiodeRFenergyharvester.sp"
   Initializing parser from header file "C:\Tanner EDA\Tanner Tools v16.3\tiburonda\models\VAdatabase.sp"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\schottky_diode(40v,30mA).md"

Start of withdiodeRFenergyharvester.sp

General options:
        threads = 1

 Device and node counts:
              Diodes -       1
          Capacitors -       2
           Resistors -       2
```

```
           Inductors -        3
    Mutual inductors -        1
     Voltage sources -        2
                VCVS -        1
  Subckt Definitions -        1
    Subckt Instances -        0
   Model Definitions -        1
     Computed Models -        1
   Independent nodes -       10
      Boundary nodes -        3
         Total nodes -       13

  Opening simulation database "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\RF_Harvester_design\withdiodeRFenergyharvester\withdiodeRFenergyharvester.

Power Results

RR2 from time 0 to 0.002
Average power consumed -> 1.975359e-004 watts
Max power 1.489073e-003 at time 0.00125032
Min power 0.000000e+000 at time 0
```

```
Measure information will be written to file "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\RF_Harvester_design\withdiodeRFenergyharvester\withdiodeRFene

Measurement result summary
  tdelay          =  -66.3000u


Parsing                      0.01 seconds
Setup                        0.02 seconds
DC operating point           0.03 seconds
Transient Analysis          10.62 seconds
Output                       0.56 seconds
-----------------------------------------
Total                       11.23 seconds

Simulation completed
```

Fig 4.2: Screenshot of Status of Simulation

The above figure primarily shows devices, node counts and the measurement result summary including time delay.

The output waveforms corresponding to the given inputs have been depicted below.

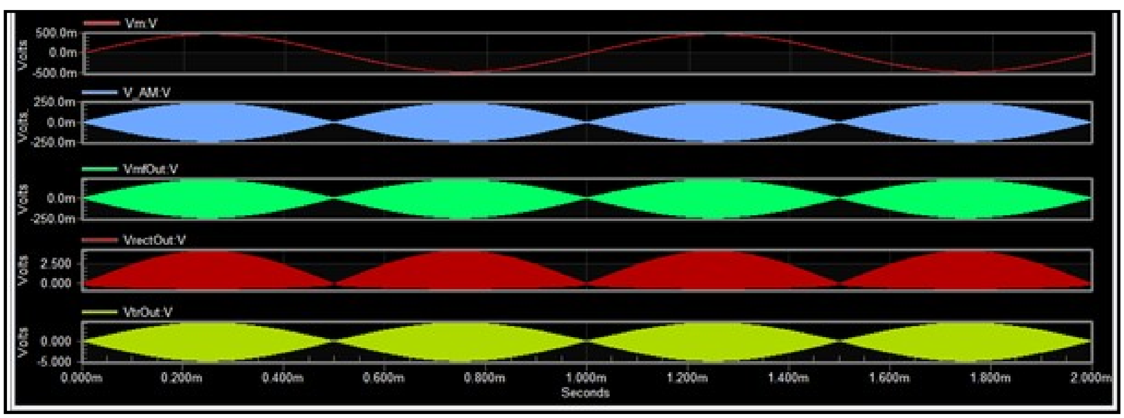



Fig 4.3: Simulation Results in W-Edit

The first waveform represents the message signal. The second waveform is the amplitude modulation signal which acts as the input to the RF energy harvester module. The waveform at the transformer's primary and secondary sides are represented by third and fifth waveform respectively. The final output of the RF EHS i.e. the rectified output is shown by the fourth waveform. The output waveform of the RF EHS corresponding to 11 KΩ load resistance is shown in Fig 4.3.

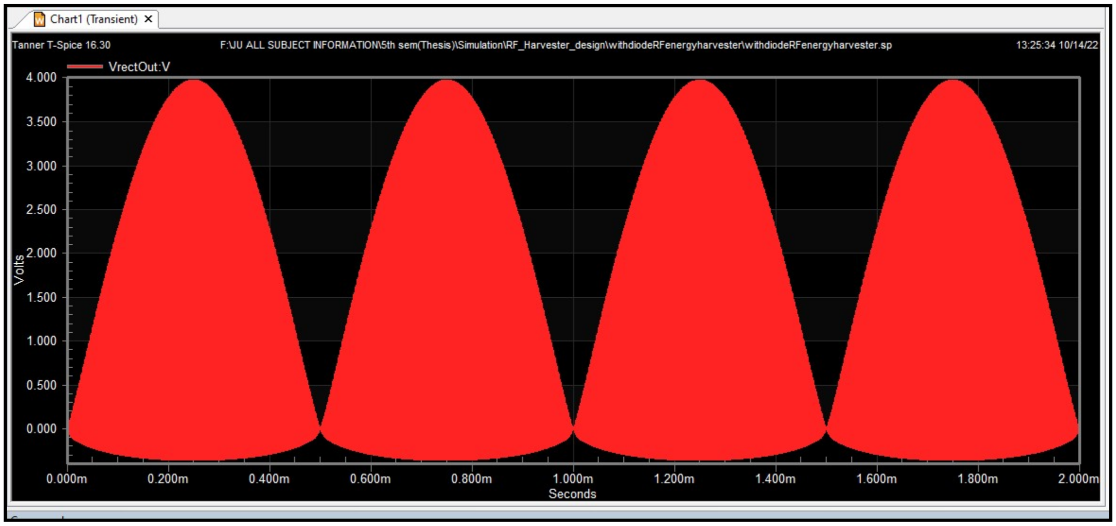



Fig 4.4: Output Dc Voltage with respect to Time

Fig 4.4 shows the existing design can offer an output dc voltage of 11 kΩ as evident from above figure.

## 4.5. Simulation Results Modified RF Energy Harvesting System using P-N Junction Diode

The simulation results of the modified RF energy harvesting system using p-n junction diode have been presented here. The screenshot of T-Spice code corresponding to this design has been shown below.

```
********* Simulation Settings - General Section *********
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\pn_diode_1.md"

***** Top Level *****
CC1 VmfOut Gnd  38.23n $ $x=1200 $y=100 $w=400 $h=600 $r=90
CCL VrectOut Gnd  10p $ $x=2600 $y=100 $w=400 $h=600 $r=90
RR1 V_AM N_1  R=2.6 $ $x=300 $y=415 $w=600 $h=150
RR2 VrectOut Gnd  R=11k $ $x=2915 $y=100 $w=150 $h=600 $r=90
LL_1 N_1 VmfOut  L=499.4n $ $x=900 $y=350 $w=600 $h=100
DD VtrOut VrectOut 1N4148W $ $x=2300 $y=400 $w=600 $h=120 $r=270
LPXFMR1 VmfOut Gnd 1uH
LSXFMR1 VtrOut Gnd 400uH
KXFMR1 LPXFMR1 LSXFMR1 1 $ $x=1700 $y=105 $w=600 $h=410
VVc Vc Gnd  SIN(0 500m 800k 0 0 0) $ $x=-1100 $y=100 $w=400 $h=600
VVm Vm Gnd  SIN(0 500m 1k 0 0 0) $ $x=-1700 $y=100 $w=400 $h=600
EE1 V_AM Gnd  VOL='V(Vm)*V(Vc)' $ $x=-300 $y=100 $w=400 $h=600

********* Simulation Settings - Analysis Section *********
.tran 0.01u 2ms start=0
.print tran v(Vm) v(VmfOut) v(Vc) v(VtrOut) v(V_AM) v(VrectOut)
.print tran i(RR2)
.power RR2
.measure tran tdelay trig v(V_AM) val=.1 rise=1 targ v(VrectOut) val=.1 rise=1

********* Simulation Settings - Additional SPICE Commands *********

.end
```

Fig 4.5: Screenshot of T-Spice Code

The screenshot of post simulation design details has been presented below.

```
Input file:   rf_using_junction_diode.sp
Progress:     Simulation completed

Total nodes:    13    Active devices:   1    Independent sources:  2
Total devices:  12    Passive devices:  8    Controlled sources:   1

T-Spice - Tanner SPICE
T-Spice - Tanner SPICE
Version 16.30
Network license
Product Release ID: T-Spice Win64 16.30.20150626.02:41:53
Copyright © 1988-2015 Mentor Graphics Corporation

   Parsing "C:\Users\USER\AppData\Local\Temp\rf_using_junction_diode.sp"
   Initializing parser from header file "C:\Tanner EDA\Tanner Tools v16.3\tiburonda\models\VAdatabase.sp"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\pn_diode_1.md"

Start of rf_using_junction_diode.sp

General options:
        threads = 1

 Device and node counts:
              Diodes -        1
          Capacitors -        2
           Resistors -        2
```

```
          Inductors -        3
   Mutual inductors -        1
    Voltage sources -        2
               VCVS -        1
  Subckt Definitions -       1
   Subckt Instances -        0
   Model Definitions -       1
    Computed Models -        1
  Independent nodes -       10
     Boundary nodes -        3
        Total nodes -       13

   Opening simulation database "C:\Users\USER\AppData\Local\Temp\rf_using_junction_diode.tsim"

Power Results

RR2 from time 0 to 0.002
Average power consumed -> 2.104664e-004 watts
Max power 1.749383e-003 at time 0.000750942
Min power 0.000000e+000 at time 0
```

```
Measure information will be written to file "C:\Users\USER\AppData\Local\Temp\rf_using_junction_diode\rf_using_junction_diode.measure"

Measurement result summary
   tdelay          =  -70.0098u


Parsing                      0.01 seconds
Setup                        0.02 seconds
Transient Analysis           9.11 seconds
Output                       0.61 seconds
-----------------------------------------
Total                        9.29 seconds

Simulation completed
```

Fig 4.6: Screenshot of Status of Simulation

The above figure primarily shows devices, node counts and the measurement result summary including time delay.

The output waveforms corresponding to the given inputs have been depicted below.

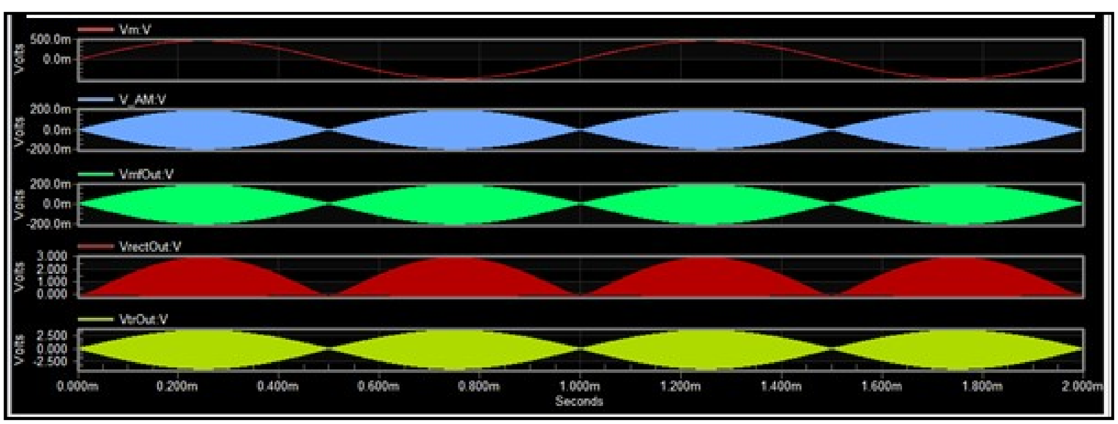



Fig 4.7: Simulation Results in W-Edit

The first waveform represents the message signal. The second waveform is the amplitude modulation signal which acts as the input to the RF energy harvester module. The waveform at the transformer's primary and secondary sides are represented by third and fifth waveform respectively. The final output of the RF EHS i.e. the rectified output is shown by the fourth waveform. The output waveform of the RF EHS corresponding to 11 KΩ load resistance is shown in Fig 4.7.

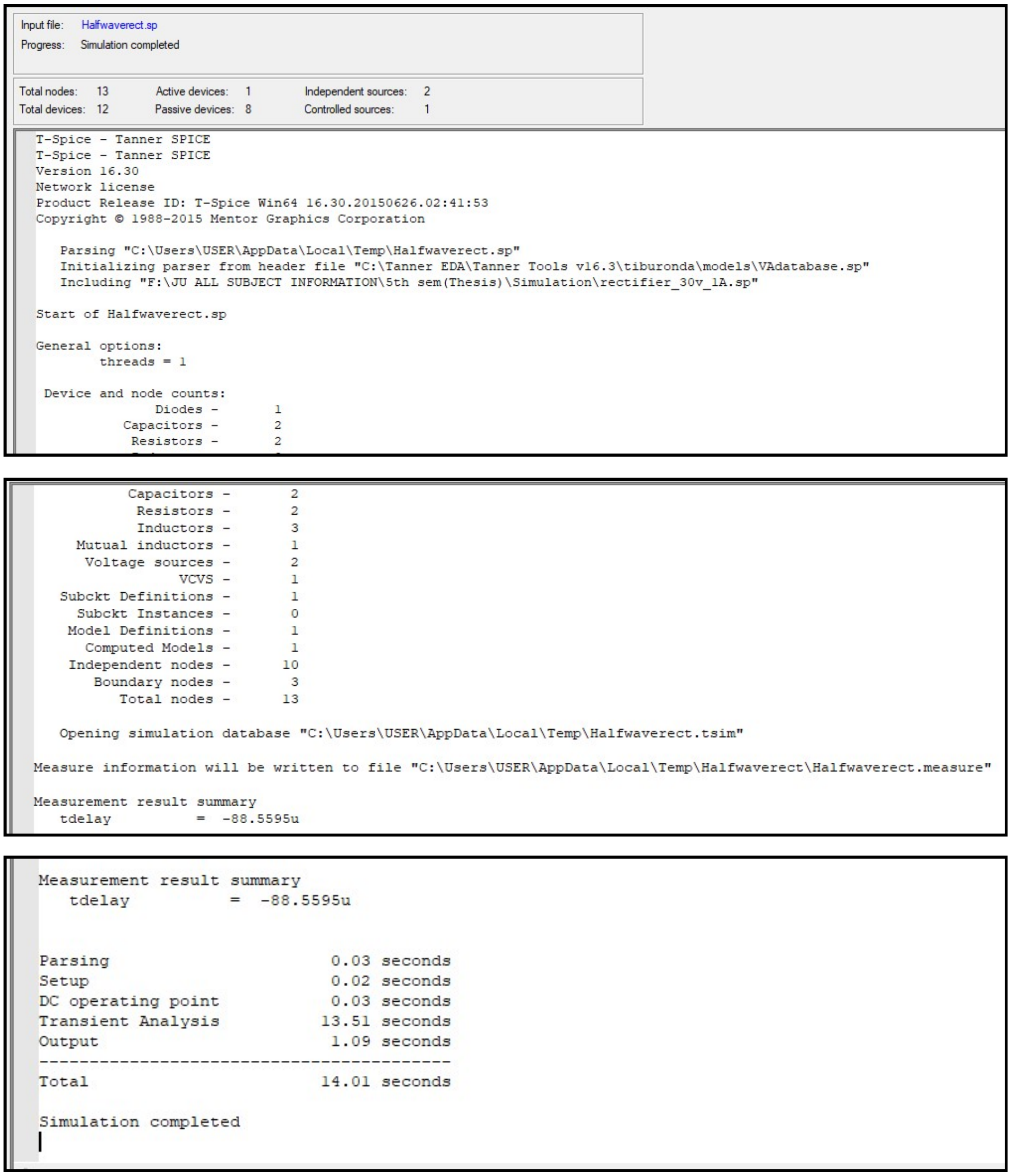
## 4.6. Simulation Results Modified RF Energy Harvesting System using Half Wave Rectifier Model

The simulation results of the modified RF energy harvesting system using half wave rectifier have been presented here. The screenshot of T-Spice code corresponding to this design has been shown below.

```
********* Simulation Settings - General Section *********
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\rectifier_30v_1A.sp"

***** Top Level *****
CC1 VrectOut Gnd  300p $ $x=3400 $y=-300 $w=400 $h=600 $r=90
CC2 VmfOut Gnd  38.23n $ $x=1300 $y=-300 $w=400 $h=600 $r=90
RR1 VrectOut Gnd  R=11k $ $x=3715 $y=-300 $w=150 $h=600 $r=90
RR2 V_AM N_1  R=2.6 $ $x=100 $y=15 $w=600 $h=150
LInductor_1 N_1 VmfOut  L=499.4n $ $x=900 $y=-50 $w=600 $h=100
DDiode_1 VtrOut VrectOut SBR130S3 $ $x=2900 $y=0 $w=600 $h=120 $r=270
LPXFMR1 VmfOut Gnd 1uH
LSXFMR1 VtrOut Gnd 400uH
KXFMR1 LPXFMR1 LSXFMR1 1 $ $x=1900 $y=-295 $w=600 $h=410
VVc Vc Gnd  SIN(0 500m 800k 0 0 0) $ $x=-900 $y=-300 $w=400 $h=600
VVm Vm Gnd  SIN(0 500m 1k 0 0 0) $ $x=-1400 $y=-300 $w=400 $h=600
EE1 V_AM Gnd  VOL='V(Vm)*V(Vc)' $ $x=-400 $y=-300 $w=400 $h=600

********* Simulation Settings - Analysis Section *********
.tran 0.01u 2m start=0m
.print tran v(Vm) v(VmfOut) v(Vc) v(VtrOut) v(V_AM) v(VrectOut)
.print tran i(RR2)
.measure tran tdelay trig v(V_AM) val=.1 rise=1 targ v(VrectOut) val=.1 rise=1
********* Simulation Settings - Additional SPICE Commands *********

.end
```

Fig 4.8: Screenshot of T-Spice Code

The screenshot of post simulation design details has been presented below.



```
Input file:   Halfwaverect.sp
Progress:   Simulation completed

Total nodes:   13     Active devices:   1     Independent sources:   2
Total devices:   12     Passive devices:   8     Controlled sources:   1

T-Spice - Tanner SPICE
T-Spice - Tanner SPICE
Version 16.30
Network license
Product Release ID: T-Spice Win64 16.30.20150626.02:41:53
Copyright © 1988-2015 Mentor Graphics Corporation

   Parsing "C:\Users\USER\AppData\Local\Temp\Halfwaverect.sp"
   Initializing parser from header file "C:\Tanner EDA\Tanner Tools v16.3\tiburonda\models\VAdatabase.sp"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\rectifier_30v_1A.sp"

Start of Halfwaverect.sp

General options:
        threads = 1

 Device and node counts:
              Diodes -       1
          Capacitors -       2
           Resistors -       2
```

```
          Capacitors -       2
           Resistors -       2
           Inductors -       3
    Mutual inductors -       1
     Voltage sources -       2
                VCVS -       1
  Subckt Definitions -       1
    Subckt Instances -       0
   Model Definitions -       1
     Computed Models -       1
   Independent nodes -      10
      Boundary nodes -       3
         Total nodes -      13

   Opening simulation database "C:\Users\USER\AppData\Local\Temp\Halfwaverect.tsim"

Measure information will be written to file "C:\Users\USER\AppData\Local\Temp\Halfwaverect\Halfwaverect.measure"

Measurement result summary
   tdelay          =  -88.5595u
```

```
Measurement result summary
   tdelay          =  -88.5595u


Parsing                         0.03 seconds
Setup                           0.02 seconds
DC operating point              0.03 seconds
Transient Analysis             13.51 seconds
Output                          1.09 seconds
-----------------------------------------
Total                          14.01 seconds

Simulation completed
```

Fig 4.9: Screenshot of Status of Simulation

The above figure primarily shows devices, node counts and the measurement result summary including time delay.

The output waveforms corresponding to the given inputs have been depicted below.

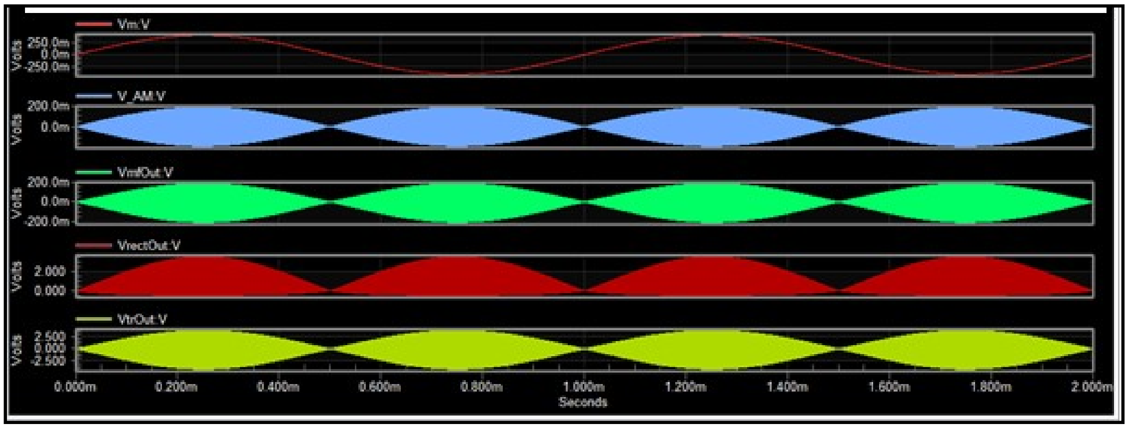



Fig 4.10: Simulation results in W-Edit

The first waveform represents the message signal. The second waveform is the amplitude modulation signal which acts as the input to the RF energy harvester module. The waveform at the transformer's primary and secondary sides are represented by third and fifth waveform respectively. The final output of the RF EHS i.e. the rectified output is shown by the fourth waveform. The output waveform of the RF EHS corresponding to 11 KΩ load resistance is shown in Fig 4.10.

## 4.7. Simulation Results Proposed RF Energy Harvesting System using NMOS Based Schottky Diode

The simulation results of the proposed RF energy harvesting system using NMOS based Schottky diode have been presented here. The screenshot of T-Spice code corresponding to this design has been shown below.

```
********* Simulation Settings - General Section *********
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\MOS(0.18u).md"
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\pn_diode_1.md"

***** Top Level *****
CC1 VmfOut Gnd  38.23n $ $x=2200 $y=100 $w=400 $h=600 $r=90
CC2 VrectOut Gnd  10p $ $x=3900 $y=100 $w=400 $h=600 $r=90
RR1 V_AM N_1  R=2.6 $ $x=1100 $y=415 $w=600 $h=150
RR2 VrectOut Gnd  R=11k $ $x=4315 $y=100 $w=150 $h=600 $r=90
LInductor_1 N_1 VmfOut  L=499.4n $ $x=1900 $y=350 $w=600 $h=100
MNMOS_1 VrectOut VtrOut VtrOut VtrOut NMOS W=2.5u L=250n AS=2.25p PS=6.8u AD=2.25p PD=6.8u $ $x=3600 $y=-700 $w=600 $h=400 $r=90
DDiode_1 VtrOut VrectOut 1N4148W $ $x=3600 $y=-1100 $w=600 $h=120 $r=270
LPXFMR1 VmfOut Gnd 1uH
LSXFMR1 VtrOut Gnd 400uH
KXFMR1 LPXFMR1 LSXFMR1 1 $ $x=2800 $y=105 $w=600 $h=410
VVc Vc Gnd  SIN(0 500m 800k 0 0 0) $ $x=0 $y=100 $w=400 $h=600
VVm Vm Gnd  SIN(0 500m 1k 0 0 0) $ $x=-500 $y=100 $w=400 $h=600
EE1 V_AM Gnd  VOL='V(Vm)*V(Vc)' $ $x=600 $y=100 $w=400 $h=600

********* Simulation Settings - Analysis Section *********
.tran 0.01u 2m start=0
.print tran v(Vm) v(VmfOut) v(Vc) v(VtrOut) v(V_AM) v(VrectOut)
.print tran i(RR2)
.power RR2
.measure tran tdelay trig v(V_AM) val=.1 rise=1 targ v(VrectOut) val=.1 rise=1

********* Simulation Settings - Additional SPICE Commands *********

.end
```

Fig 4.11: Screenshot of T-Spice Code

The screenshot of post simulation design details has been presented below.

```
Input file:   RF_energy_harvester_diodeUsingNmos.sp
Progress:     Simulation completed

Total nodes:    13     Active devices:   2     Independent sources:   2
Total devices:  13     Passive devices:  8     Controlled sources:    1

T-Spice - Tanner SPICE
T-Spice - Tanner SPICE
Version 16.30
Network license
Product Release ID: T-Spice Win64 16.30.20150626.02:41:53
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   Parsing "C:\Users\USER\AppData\Local\Temp\RF_energy_harvester_diodeUsingNmos.sp"
   Initializing parser from header file "C:\Tanner EDA\Tanner Tools v16.3\tiburonda\models\VAdatabase.sp"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\MOS(0.18u).md"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\pn_diode_1.md"

Start of RF_energy_harvester_diodeUsingNmos.sp
Loaded BSIM3v31 model library, Berkeley BSIM3 v3.1.0 with extensions

General options:
        threads = 1

 Device and node counts:
                MOSFETs -        1
```
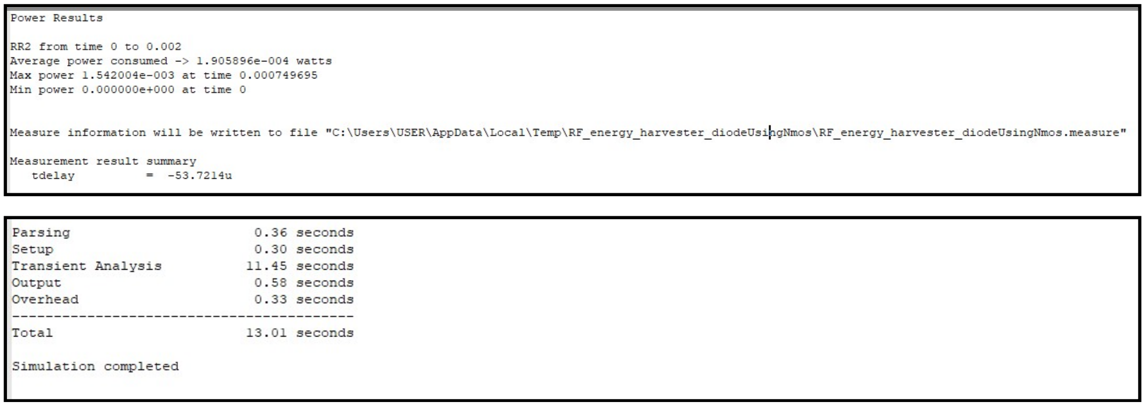

```
     MOSFET geometries -        1
                Diodes -        1
            Capacitors -        2
             Resistors -        2
             Inductors -        3
      Mutual inductors -        1
       Voltage sources -        2
                  VCVS -        1
    Subckt Definitions -        1
      Subckt Instances -        0
     Model Definitions -        3
       Computed Models -        2
     Independent nodes -       10
        Boundary nodes -        3
           Total nodes -       13

 Opening simulation database "C:\Users\USER\AppData\Local\Temp\RF_energy_harvester_diodeUsingNmos.tsim"
```



```
Power Results

RR2 from time 0 to 0.002
Average power consumed -> 1.905896e-004 watts
Max power 1.542004e-003 at time 0.000749695
Min power 0.000000e+000 at time 0

Measure information will be written to file "C:\Users\USER\AppData\Local\Temp\RF_energy_harvester_diodeUsingNmos\RF_energy_harvester_diodeUsingNmos.measure"

Measurement result summary
   tdelay          =  -53.7214u
```

```
Parsing                          0.36 seconds
Setup                            0.30 seconds
Transient Analysis              11.45 seconds
Output                           0.58 seconds
Overhead                         0.33 seconds
-------------------------------------------------
Total                           13.01 seconds

Simulation completed
```

Fig 4.12: Screenshot of Status of Simulation

The above figure primarily shows devices, node counts and the measurement result summary including time delay.

The output waveforms corresponding to the given inputs have been depicted below.

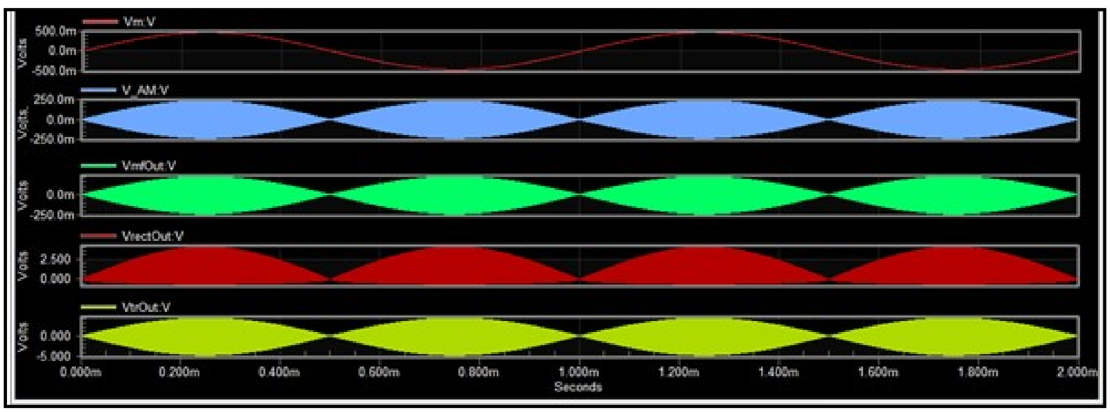



Fig 4.13: Simulation Results in W-Edit

The first waveform represents the message signal. The second waveform is the amplitude modulation signal which acts as the input to the RF energy harvester module. The waveform at the transformer's primary and secondary sides are represented by third and fifth waveform respectively. The final output of the RF EHS i.e. the rectified output is shown by the fourth waveform. The output waveform of the RF EHS corresponding to 11 KΩ load resistance is shown in Fig 4.13.

## 4.8. Simulation Results Proposed RF Energy Harvesting System using PMOS Based Schottky Diode

The simulation results of the proposed RF energy harvesting system using PMOS based schottky diode have been presented here. The screenshot of T-Spice code corresponding to this design has been shown below.

```
********* Simulation Settings - General Section *********
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\MOS(0.18u).md"
.include "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\pn_diode_1.md"

***** Top Level *****
CC1 VmfOut Gnd  38.23n $ $x=100 $y=-300 $w=400 $h=600 $r=90
CC2 VrectOut Gnd  10p $ $x=1900 $y=-400 $w=400 $h=600 $r=90
RR1 V_AM N_1  R=2.6 $ $x=-1000 $y=15 $w=600 $h=150
RR2 VrectOut Gnd  R=11k $ $x=2315 $y=-400 $w=150 $h=600 $r=90
LInductor_1 N_1 VmfOut  L=499.4n $ $x=-300 $y=-50 $w=600 $h=100
MPMOS_2 VtrOut N_2 VrectOut VrectOut PMOS W=2.5u L=250n AS=2.25p PS=6.8u AD=2.25p PD=6.8u $ $x=1400 $y=-1200 $w=600 $h=400 $r=90
DDiode_1 VtrOut VrectOut 1N4148W $ $x=1400 $y=-1600 $w=600 $h=120 $r=270
LPXFMR2 VmfOut Gnd 1uH
LSXFMR2 VtrOut Gnd 400uH
KXFMR2 LPXFMR2 LSXFMR2 1 $ $x=800 $y=-395 $w=600 $h=410
VVc Vc Gnd  SIN(0 500m 800k 0 0 0) $ $x=-2300 $y=-500 $w=400 $h=600
VVm Vm Gnd  SIN(0 500m 1k 0 0 0) $ $x=-3200 $y=-500 $w=400 $h=600
EE1 V_AM Gnd  VOL='V(Vc)*V(Vm)' $ $x=-1500 $y=-500 $w=400 $h=600

********* Simulation Settings - Analysis Section *********
.tran 0.01u 2m start=0m
.option prtdel=0
.print tran v(Vm) v(VmfOut) v(Vc) v(VtrOut) v(V_AM) v(VrectOut)
.print tran i(RR2)
.power RR2
.measure tran tdelay trig v(V_AM) val=.1 rise=1 targ v(VrectOut) val=.1 rise=1
********* Simulation Settings - Additional SPICE Commands *********
.end
```

Fig 4.14: Screenshot of T-Spice Code

The screenshot of post simulation design details has been presented below.

```
Input file:     RF_Harvester_design.sp
Progress:       Simulation completed

Total nodes:    14     Active devices:   2     Independent sources:  2
Total devices:  13     Passive devices:  8     Controlled sources:   1

T-Spice - Tanner SPICE
T-Spice - Tanner SPICE
Version 16.30
Network license
Product Release ID: T-Spice Win64 16.30.20150626.02:41:53
Copyright © 1988-2015 Mentor Graphics Corporation

   Parsing "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\RF_Harvester_design\RF_Harvester_design.sp"
   Initializing parser from header file "C:\Tanner EDA\Tanner Tools v16.3\tiburonda\models\VAdatabase.sp"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\MOS(0.18u).md"
   Including "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\pn_diode_1.md"

Start of RF_Harvester_design.sp
Loaded BSIM3v31 model library, Berkeley BSIM3 v3.1.0 with extensions
```

```
General options:
        threads = 1

Output options:
         prtdel = 0

 Device and node counts:
                MOSFETs -        1
    MOSFET geometries -        1
                 Diodes -        1
             Capacitors -        2
              Resistors -        2
              Inductors -        3
     Mutual inductors -        1
       Voltage sources -        2
                   VCVS -        1
   Subckt Definitions -        1
     Subckt Instances -        0
    Model Definitions -        3
      Computed Models -        2
```

```
    Independent nodes -      11
       Boundary nodes -       3
          Total nodes -      14
*** 1 WARNING MESSAGE GENERATED DURING SETUP


   Opening simulation database "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\RF_Harvester_design\RF_Harvester_design.tsim"

Power Results

RR2 from time 0 to 0.002
Average power consumed -> 1.975726e-004 watts
Max power 1.481383e-003 at time 0.00175095
Min power 0.000000e+000 at time 0


Measure information will be written to file "F:\JU ALL SUBJECT INFORMATION\5th sem(Thesis)\Simulation\RF_Harvester_design\RF_Harvester_design\RF_Harvester_design.m

Measurement result summary
   tdelay          =  -50.0214u
```

```
Parsing                        0.13 seconds
Setup                          0.11 seconds
DC operating point             0.01 seconds
Transient Analysis            10.78 seconds
Output                         0.55 seconds
Overhead                       0.11 seconds
-------------------------------------------
Total                         11.69 seconds
```

Fig 4.15: Screenshot of Status of Simulation

The above figure primarily shows devices, node counts and the measurement result summary including time delay.

The output waveforms corresponding to the given inputs have been depicted below.

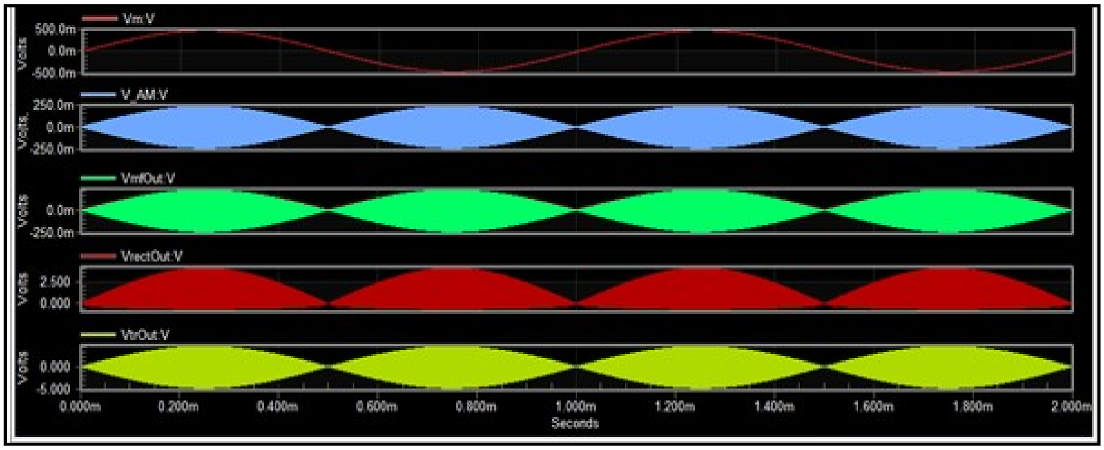



Fig 4.16: Simulation Results in W-Edit

The first waveform represents the message signal. The second waveform is the amplitude modulation signal which acts as the input to the RF energy harvester module. The waveform at the transformer's primary and secondary sides are represented by third and fifth waveform respectively. The final output of the RF EHS i.e. the rectified output is shown by the fourth waveform. The output waveform of the RF EHS corresponding to 11 KΩ load resistance is shown in Fig 4.16.

## 4.9. Comparison of Results

The comparison of the various designs in terms of different parameters such as dc output voltage and output power have been shown in Table 4.2 for various values of load resistance.

Table 4.2: Results of Simulation with respect to Output Dc Voltage and Output Power for Different Load Resistance

| **DC Output Voltage, Output Power vs Load Resistance** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **P-N Junction Diode** | | | **Rectifier Model File** | | | **Schottky Diode Model File Existing Paper [27]** | | | **NMOS based Schottky diode [30]** | | | **Modified PMOS based Schottky diode** | | |
| **R (kΩ)** | **V (Volt)** | **I** | **P (uW)** | **V (Volt)** | **I** | **P (uW)** | **V (Volt)** | **I** | **P (uW)** | **V (Volt)** | **I** | **P (uW)** | **V (Volt)** | **I** | **P (uW)** |
| 0.5 | 1.1 | 2.2 mA | 2420 | 1.2 | 2.6mA | 3120 | 1.5 | 3.2mA | 4800 | 1.6 | 3.22 mA | 5152 | 1.6 | 3.2mA | 5120 |
| 1.0 | 1.7 | 1.7 mA | 2890 | 1.8 | 2.0mA | 3600 | 2.0 | 2.3mA | 4600 | 2.3 | 2.3mA | 5290 | 2.2 | 2.3mA | 5060 |
| 1.5 | 2.0 | 1.4 mA | 2800 | 2.2 | 1.6mA | 3520 | 2.5 | 1.8mA | 4500 | 2.7 | 1.8mA | 4860 | 2.6 | 1.79 mA | 4654 |
| 2.0 | 2.1 | 1.06 mA | 2226 | 2.5 | 1.3mA | 3250 | 2.9 | 1.5mA | 4350 | 3.1 | 1.52 mA | 4712 | 3.0 | 1.51 mA | 4500 |
| 3.5 | 2.4 | 701.4uA | 1683.4 | 2.9 | 1.02 mA | 2900 | 3.4 | 973.1uA | 3308.54 | 3.5 | 1.01 mA | 3535 | 3.4 | 985.5 uA | 3350.7 |
| 5.0 | 2.6 | 522.7uA | 1359 | 3.1 | 779uA | 2414.9 | 3.6 | 723.2uA | 2603.52 | 3.7 | 751.9uA | 2782.03 | 3.6 | 730.8 uA | 2630.88 |
| 6.5 | 2.7 | 415.9uA | 1122.9 | 3.3 | 628uA | 2072.4 | 3.7 | 575.7uA | 2130.09 | 3.8 | 599.7uA | 2278.86 | 3.7 | 581.3 uA | 2150.8 |
| 8.0 | 2.8 | 346.3uA | 969.6 | 3.4 | 528uA | 1795.2 | 3.8 | 478.3uA | 1812.5 | 3.9 | 499.2uA | 1946.88 | 3.8 | 482.4 uA | 1833.1 |
| 9.5 | 2.9 | 296.5uA | 859.8 | 3.5 | 410uA | 1435 | 3.9 | 409.2uA | 1595.88 | 4.0 | 427.7uA | 1710.8 | 3.9 | 412.5 uA | 1608.75 |
| 11 | 3.0 | 259.3uA | 777.9 | 3.6 | 330uA | 1188 | 4.0 | 357.2uA | 1428.8 | 4.2 | 374.4uA | 1535.08 | 4.1 | 360.01uA | 1440.04 |

The variation of dc output voltage with load resistance for all the design has been depicted in Fig 4.17.

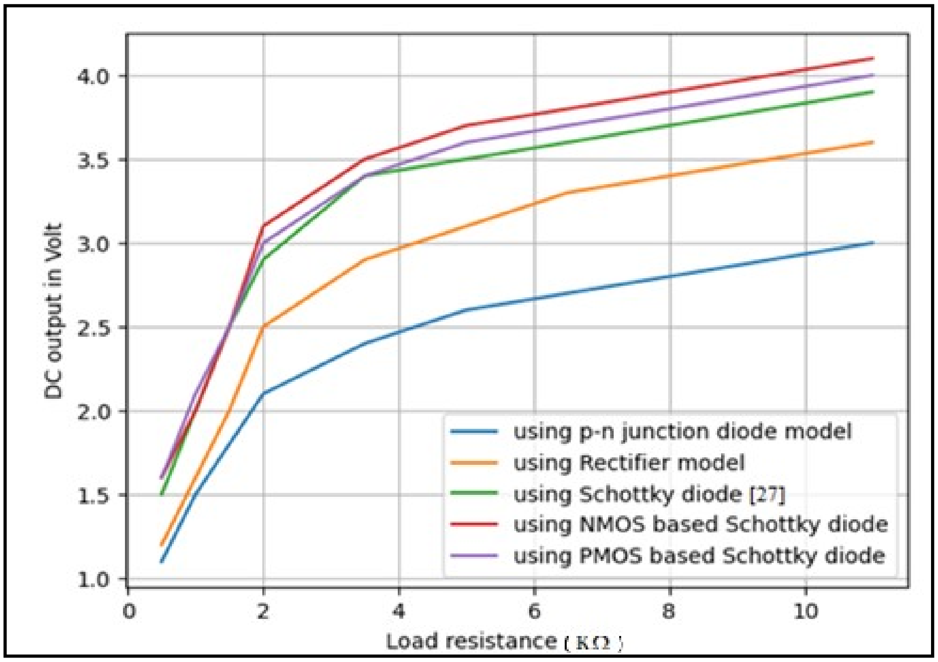



Fig 4.17: Plot of Dc Output Voltage with Load Resistance

Above figure shows that the proposed design of RF EHS using both NMOS and PMOS based Schottky diode outperforms the existing design using Schottky diode [27]. It happens because of the secondary coil of the RF transformer has an impedance of about 2009.6Ω at 800 KHz. So, maximum power transfer from the RF source to the rectifier load occurs at around $R_L$= 2 KΩ .The outcome p-n junction diode model and rectifier model (T-Spice) based designs are also presented here for the purpose of comparison.

The plots of load power with load resistance have been shown in Fig 4.18.

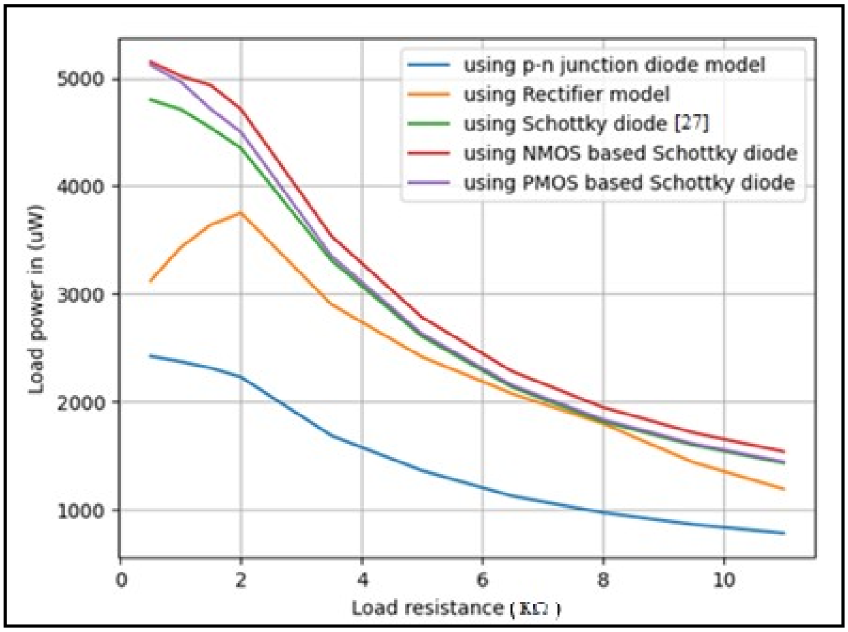



Fig 4.18: Load Power vs Load Resistance

Above figure shows that at a particular value of load resistance, say 2KΩ, the proposed design using NMOS and PMOS based on Schottky diode gives load power of 4712uW and 4500uW respectively as compared to existing design [27] which presents the load power of 4350uW. The other two design offer which lower values of lower power at the same value of load resistance.

The comparison of the various designs in terms of different parameters such as power consumption and time delay have been shown in Table 4.3 for various values of load resistance.

Table 4.3: Results of Simulation with respect to Power Consumption and Time Delay for Different Load Resistance

| Power Consumption, Time Delay vs Load Resistance | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | p-n Junction Diode | | Rectifier Model File | Schottky Diode Model File Existing Paper [27] | | NMOS based Schottky diode [30] | | Modified PMOS based Schottky diode | | |
| R (kΩ) | Power Consumption (W) | Delay (us) | Delay (us) | Power Consumption (W) | Delay (us) | Power Consumption (W) | Delay (us) | Power Consumption (W) | Delay (us) |
| 0.5 | $9.532*10^{-4}$ | 56.32 | 81.07 | $8.419*10^{-4}$ | 53.83 | $8.050*10^{-4}$ | 43.83 | $7.584*10^{-4}$ | 40.08 |
| 1.0 | $9.144*10^{-4}$ | 57.57 | 84.85 | $8.222*10^{-4}$ | 55.6 | $7.811*10^{-4}$ | 48.78 | $7.277*10^{-4}$ | 43.80 |
| 1.5 | $8.037*10^{-4}$ | 60.05 | 86.09 | $7.286*10^{-4}$ | 59.4 | $6.927*10^{-4}$ | 50.038 | $6.431*10^{-4}$ | 46.258 |
| 2.0 | $7.050*10^{-4}$ | 65.03 | 87.3 | $6.424*10^{-4}$ | 61.32 | $6.120*10^{-4}$ | 51.24 | $5.671*10^{-4}$ | 46.28 |
| 3.5 | $5.064*10^{-4}$ | 67.49 | 88.4 | $4.657*10^{-4}$ | 63.75 | $4.463*10^{-4}$ | 51.29 | $4.147*10^{-4}$ | 47.52 |
| 5.0 | $3.936*10^{-4}$ | 67.53 | 88.53 | $3.644*10^{-4}$ | 63.80 | $3.504*10^{-4}$ | 52.51 | $3.283*10^{-4}$ | 48.75 |
| 6.5 | $3.222*10^{-4}$ | 68.76 | 88.543 | $2.998*10^{-4}$ | 64.99 | $2.887*10^{-4}$ | 52.52 | $2.772*10^{-4}$ | 48.76 |
| 8.0 | $2.731*10^{-4}$ | 68.78 | 88.552 | $2.552*10^{-4}$ | 65.02 | $2.459*10^{-4}$ | 52.533 | $2.417*10^{-4}$ | 49.96 |
| 9.5 | $2.374*10^{-4}$ | 69.99 | 88.557 | $2.225*10^{-4}$ | 65.03 | $2.145*10^{-4}$ | 52.537 | $2.167*10^{-4}$ | 49.98 |
| 11 | $2.104*10^{-4}$ | 70.01 | 88.5505 | $1.975*10^{-4}$ | 65.04 | $1.905*10^{-4}$ | 53.72 | $1.915*10^{-4}$ | 50.02 |

The power consumption related to the different designs (using T-Spice) for various load resistance is shown in Fig 4.19.

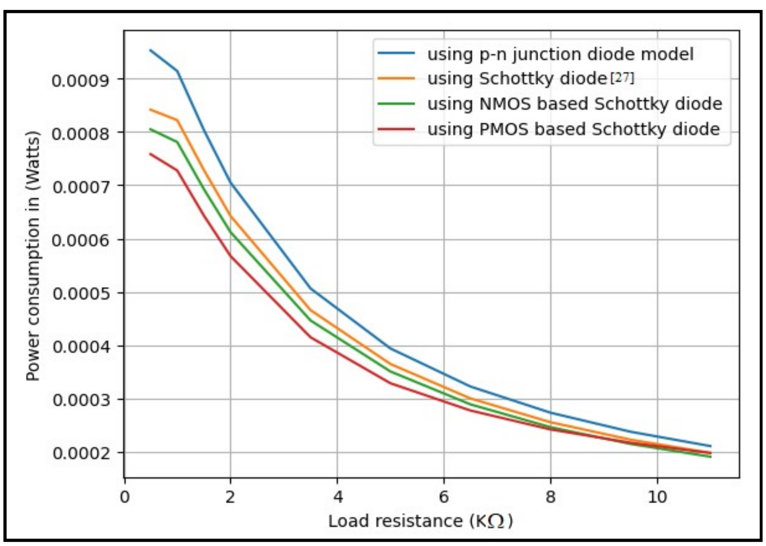



Fig 4.19: Power Consumption vs Load Resistance

Above figure shows the proposed MOS based designs of Schottky diode used in rectifier circuit provides the lower values of power consumption as compared to other designs. For example, at a load resistance of 2KΩ, the PMOS and NMOS based designs offer a power consumption of $5.671*10^{-4}$ and $6.120*10^{-4}$ respectively. At the same value of the load resistance, the power consumption values corresponding to the designs involving existing Schottky diode and p-n junction diode are $6.424*10^{-4}$ and $7.050*10^{-4}$ respectively. So, PMOS based design can be considered as the best solution as far as time delay is concerned as it offers the least amount of time delay, thus proving the faster operation of the design.

The delay generated by T-Spice for each design has been observed with respect to load resistance and presented in Fig 4.20.

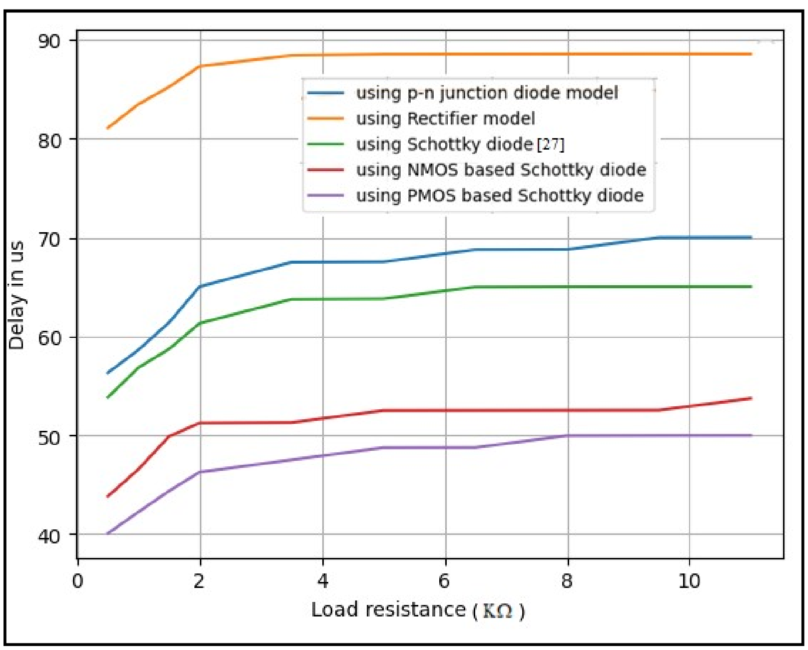



Fig 4.20: Time Delay vs Load Resistance

Above figure shows the proposed MOS based designs of Schottky diode used in rectifier circuit provides the lower values of time delay as compared to other designs. For example, at a load resistance of 2KΩ, the PMOS and NMOS based designs offer a time delay of 46.28us and 51.24us respectively. At the same value of the load resistance, the time delay values corresponding to the designs involving existing Schottky diode, p-n junction diode and rectifier model are 61.32us, 65.03us, and 87.3us respectively. So, PMOS based design can be considered as the best solution as far as time delay is concerned as it offers the least amount of time delay, thus proving the faster operation of the design.

## 4.10. Comparative Table and Corresponding Analysis

The above results of comparison have been summarized below in Table 4.4, 4.5, 4.6, 4.7.

Table 4.4: Voltage Measurement of Proposed Work and Existing RF EHS

| **Various model of diode** | **0.5 kΩ** | **11 kΩ** |
|---|---|---|
| p-n junction diode [% deterioration] | 26.66% | 25% |
| Rectifier model [% deterioration] | 20% | 10% |
| NMOS based Schottky diode [% improvement] | 6.66% | 5% |
| PMOS based Schottky diode [% improvement] | 6.66% | 2.5% |

Table 4.5: Output Power Measurement of Proposed Work and Existing RF EHS

| **Various model of diode** | **0.5 kΩ** | **11 kΩ** |
|---|---|---|
| p-n junction diode [% deterioration] | 49.58% | 45.55% |
| Rectifier model [% deterioration] | 35% | 16.85% |
| NMOS based Schottky diode [% improvement] | 7.33% | 7.43% |
| PMOS based Schottky diode [% improvement] | 6.66% | 0.78% |

Table 4.6: Power Consumption of Proposed Work and Existing RF EHS

| **Various model of diode** | **0.5 kΩ** | **11 kΩ** |
|---|---|---|
| p-n junction diode [% deterioration] | 0.13% | 0.06% |
| NMOS based Schottky diode [% improvement] | 0.04% | 0.04% |
| PMOS based Schottky diode [% improvement] | 0.09% | 0.03% |

Table 4.7: Delay Measurement of Proposed Work and Existing RF EHS

| **Various model of diode** | **0.5 kΩ** | **11 kΩ** |
|---|---|---|
| p-n junction diode [% deterioration] | 4.2% | 7.64% |
| Rectifier model [% deterioration] | 33.60% | 26.55% |
| NMOS based schottky diode [% improvement] | 18.57% | 17.40% |
| PMOS based schottky diode [% improvement] | 25.54% | 23.09% |

The table 4.4 shows that the proposed NMOS based Schottky diode and PMOS based Schottky diode design shows an improvement of 6.66% and 6.66% respectively at a load resistance 0.5 kΩ and 5% and 2.5% at a load resistance of 11 kΩover the existing design [27] as far as measured dc voltage is concerned. It is clear that both p-n junction diode based design and rectifier model based design offers considerable degradation in terms of output dc voltage.

The table 4.5 shows that the proposed NMOS based Schottky diode and PMOS based Schottky diode design shows an improvement of 7.33% and 6.66% respectively at a load resistance 0.5 kΩ and 7.43% and 0.78% at a load resistance of 11 kΩ over the existing design [27] as far as measured consumed power is concerned. It is clear that both p-n junction diode based design and rectifier model based design offers considerable degradation in terms of power consumption.

The table 4.6 shows that the proposed NMOS based Schottky diode and PMOS based Schottky diode design shows an improvement of 0.04% and 0.09% respectively at a load resistance 0.5 kΩ and 0.04% and 0.03% at a load resistance of 11 kΩ over the existing design [27] as far as measured power consumption is concerned. It is clear that both p-n junction diode based design and rectifier model based design offers considerable degradation in terms of time delay.

The table 4.7 shows that the proposed NMOS based Schottky diode and PMOS based Schottky diode design shows an improvement of 18.57% and 25.54% respectively at a load resistance 0.5 kΩ and 17.40% and 23.09% at a load resistance of 11 kΩ over the existing design [27] as far as measured time delay is concerned. It is clear that both p-n junction diode based design and rectifier model based design offers considerable degradation in terms of time delay.

## 4.11. Discussion

In this chapter, the suggested system model is simulated using Tanner EDA 16.30 and the overall performance is examined and compared using various model of diode. The effectiveness of the proposed work of designing of RF EHS is investigated and compared to the existing work. Study and comparison of the dc output voltage, output power, time delay and power consumption for various values of load resistance is observed. Performance assessments of the output dc voltage, output power, time delay and power consumption is done, as shown by a comparison of the outage performance in Table 4.4, Table 4.5, Table 4.6 and Table 4.7 respectively.

# CHAPTER 5

# CONCLUSION

## 5.1. Concluding Remarks

In this thesis, the benefits of designing RF EHS in less area have been proposed based on different technologies. Design is carried out using various model file of diode and MOS based Schottky diode using T-Spice. The results have been analyzed using W-Edit in terms of dc output voltage, output power, power consumption, time delay. The performance of designing RF EHS using p-n junction diode model, rectifier model, NMOS based Schottky diode, PMOS based Schottky diode has been compared with existing model.

Our findings from the simulation results are given below:

The performance of the proposed work in terms of dc output voltage, output power (Table 4.2) and power consumption, time delay (Table 4.3) are analyzed. The efficiency of dc output voltage (Table 4.4), output power (Table 4.5), power consumption (Table 4.6), and time delay (Table 4.7) of the proposed work are compared with respect to the existing work. It is seen that the modified model using p-n junction diode model and rectifier model consumes less power and offers less time delay than the existing model. But both of these designs provide less dc output voltage and output power than the existing model.

It is also observed that design using MOS technology (both PMOS & NMOS), the output dc voltage and output power are higher than the existing work. Also, power consumption and time delay are lower as compared to the existing model. In other words, it can be summarized that the proposed design of RF EHS using MOS technology offers the best solution out of which, the PMOS based RF EHS provides the best alternative.

## 5.2. Future Extensions

The work presented in this thesis can be extended further in the following directions:

The design can be carried out using other circuit simulator platforms like Cadence, SILVACO etc. and performance can be compared with others. FPGA implementation of the design can be carried out to have a clear idea about the resource usage of the design. It can be extended to on-chip using MOS technology. Also, by lowering the scaling of MOS technology, the design can be improved to have high speed and low power consumption leading to a more efficient design. The design can also be modified with full wave rectifier circuit to have higher output dc voltage and output power. This will require high power consumption and time delay. Hence an optimal design of RF EHS can be carried out by trading off different design parameters.

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