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Original Research Article

Development of a Radio Frequency Rectifier Circuit for Radio Frequency Energy Harvesting

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ABSTRACT

The aim of this work is to develop a radio frequency rectifier circuit for radio frequency energy harvesting that can produce voltage from ambient radio frequency (RF) signal to energize low powered sensor devices or Internet of Things networks. The radio frequency rectifier was first designed and simulated in Proteus CAD software environment in other to assess the circuits theoretical performance. The designed circuit was then developed on a vero board and the power conversion efficiency of the circuit was evaluated. The rectifier circuit was simulated, and its performance evaluated under various input condition. The rectifier circuit was also simulated with a boost converter circuit attached to the output and the output voltage improved significantly by about 321%. The maximum voltage output from the developed rectifier circuit was 0.29V. The power conversion efficiency of the developed radio frequency rectifier circuit was evaluated to be 40%. It is highly recommended that further works should be done on optimizing the receiving antenna and the impedance matching network of the RF energy harvester.

1. INTRODUCTION

The demand for sustainable and autonomous energy solutions has rapidly increased with the growth of wireless sensor networks, the Internet of Things (IoT), and low-power electronic devices (Wolff, 2021). As these devices proliferate, the need for reliable power sources that can operate without frequent battery replacement becomes critical, especially in remote or hard-to-reach environments (Wolff, 2021). In such cases, radio frequency energy harvesting (RFEH) has emerged as a promising technology, capable of converting ambient RF energy into usable electrical power to support low-energy devices such as wireless sensors, radio frequency identification (RFID) systems, and other low-power electronics. (Muhammad, et al., 2024).

Radio frequency energy is constantly emitted into the environment from various sources, such as mobile communication towers, Wi-Fi routers, television broadcast stations, and other wireless communication systems. Although the amount of energy available in these ambient RF signals is relatively small compared to solar or mechanical energy sources, advancements in energy harvesting circuits, particularly rectifiers, have made it possible to capture and convert this energy into a usable form (Alzamil and Islam, 2022).

The receiving side of RF energy harvesting systems generally include receiving antenna, matching network, rectification circuit and power management unit (Muhammad, et al., 2022). The receiving antenna and the rectifier when combined, are defined as a rectenna (Ziyue et al, 2022). Performance of RFEH significantly depends on the radiation performance of the receiving antenna. The antenna is the key element of a rectenna that determines the performance of RFEH or wireless power transfer (WPT), as the antenna is required to capture RF signals (Ullah, 2022).

This work focuses on the design and optimization of a radio frequency rectifier circuit, with the goal of maximizing the power conversion efficiency (PCE) and determining the potential applications for RF energy harvesting in real-world scenarios (Ziyue et al, 2022). According to Bouchouicha et al. (2010), the concept of RF energy harvesting involves capturing ambient RF signals using an antenna, converting the RF energy into direct current (DC) using a rectifier circuit, and storing or using the resulting energy to power low-consumption devices. One of the key components of this process is the rectifier, which is responsible for converting the alternating current (AC) signal from RF waves into a steady DC output. The efficiency of this rectification process is critical for maximizing the amount of energy that can be harvested.

The capacity to transform ambient signals into practical DC power day and night, indoors and out, is one benefit of RF energy harvesting. RF signals are an excellent fit for indoor applications because they can pass through restricted areas and opaque walls (Alzamil and Islam, 2022). In addition, wearable and portable applications are made possible by the lightweight and compact design of RF energy harvesting devices. Hybrid energy harvesting systems can be achieved by combining different ambient energy harvesting technologies, such as solar cells, with different types of antennas. RF energy harvester circuits have the potential to energize low-power electronic devices instead of chemical batteries which contain heavy metals that can pollute the environment and are impossible to change or recharge. RF energy harvesters are much less affected by weather conditions compared to other energy harvesting systems (Yunus, 2016). The RFEH system works using the following procedures- first an antenna receives the RF-power, the received power or signals is then converted by a rectifier to a (direct current) DC voltage. A matching network is incorporated to maximize the power transfer that is to transfer the power captured by the antenna to the rectifier without loss. A boost converter is then used to boost the output voltage of the rectifier which is typically low. The amplified voltage is then held in a DC storage and this will act as the power source for the load intended. In RF energy harvesting systems, the rectifier circuit plays a crucial role by converting the captured alternating current (AC) RF signal into a DC output, which can then be used to power electronic devices or recharge batteries. Since the AC signals received by the antenna are typically low in power, the rectifier must be designed to maximize efficiency and ensure that minimal energy is lost during the conversion process. This step is vital for achieving a high-power conversion efficiency (PCE), which is a key performance metric in energy harvesting systems (Xu et al., 2022). The study of Khan, et al., (2024) reported the results of the PCE's of different RF rectifier circuits from various research works.

RF energy harvesting has diverse applications across fields where low-power, maintenance-free operation is critical. These applications leverage the ambient RF energy from sources such as mobile network signals, Wi-Fi routers, and broadcast stations, enabling devices to operate sustainably without relying on conventional batteries (Ren et al., 2020); (Lu, et al., 2015). Application areas include Internet of Things (IoT), Biomedical Implants, Wearable devices, Security Surveillance, and Precision agriculture.

According to Khan et. al. (2024) in other to increase the level of output DC voltage, it is essential to increase the number of stages in the rectifier and this leads to huge voltage drops and degrades the overall PCE and sensitivity of the rectifier. Previous works have considered using a smaller number of rectifier stages such as one, two or three stages and non from the literatures reviewed have put into design consideration, by incorporating a diode with a low forward voltage drop in other to minimize the huge voltage drops that may arise from increased number of stages (Khan et al., 2024). This work entails a seven stage RF rectifier using BAT 45 Schottky diode which is known for its low forward voltage drop of 150-450 mV (Elprocus, 2024). This design approach increases the PCE and the sensitivity of the RF rectifier without much trade-off to the voltage output of the circuit.

2. MATERIALS AND METHODS

2.1. RF Rectifier Circuit Design and Development

Chen and Chiu (2017) presented an analyses that multiple-stages rectifiers produces an output voltage that is higher, moreover the power conversion efficiency is maximum in the half-wave rectifier, but this is independent on the frequency, this is due to the fact that the losses as a result of the voltage are minimized since many components are present. Generally, the RF energy harvester can be obtained by connecting the antenna equivalent circuit to a rectifier. Figure 1 shows the description.

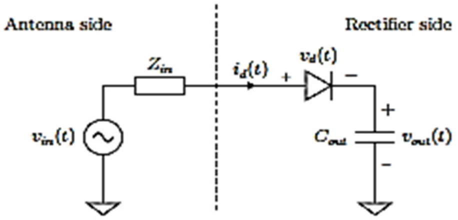

Figure 1: RF energy harvester basic circuit

The output voltage of the circuit can be expressed as a function of the product of V_{out} (output voltage of single stage's rectifier) and N (number of stages in the rectifiers) as shown in Equation 1 (Khan et. al., 2024). A seven-stage rectifier circuit is chosen whose schematic is shown in Figure 2. With 7 stages, the circuit can multiply the output voltage from a single stage by approximately seven times, significantly increasing the DC output voltage.

$$V_{out,n} = N \times V_{out} \tag{1}$$

Where: V_{out} = output voltage of single stage's rectifier and N = 7 (number of stages)

This higher voltage is particularly beneficial for powering devices that require higher DC levels or for further processing by components like boost converters, which can efficiently operate with higher input voltages. In RF energy harvesting, input power levels are typically low. A 7-stage rectifier as shown in Figure 2 can effectively accumulate and multiply the available energy over more stages, enhancing the overall energy harvesting efficiency. By distributing the voltage multiplication across seven stages, each diode and capacitor operates within optimal parameters, reducing individual component stress and improving the overall circuit efficiency. The power conversion efficiency is defined as shown in Equation 2 (Khan et. al., 2024):

$$\eta_{rec} = \frac{V_o^2}{P_{in} \times R_L} \times 100\ (\%) \tag{2}$$

Where P_{in} is input RF power, V_o is output DC voltage, R_L is output load resistance and η_{rec} is the rectifier power conversion efficiency.

2.2. Basic Setup of the RF Energy Harvester in Proteus

The circuit design and simulation was carried out using proteus software to evaluate performance of the circuit at a center frequency of 950 MHz in other to optimize the design and identify potential issues. Figure 2 illustrates the RF-to-DC harvester circuit, where the sine wave source has been used to model the receiving antenna operating at 950 MHz, the voltage multiplier circuit was simulated with BAT 45 Schottky diode and also the multiplier circuit incorporates a 1nF capacitor. Also, the output of the RF-harvester circuit has been connected to a 1nF capacitor and a 1k load resistor in parallel to improve the voltage regulation and reduce the ripple and noise generated from the circuit.

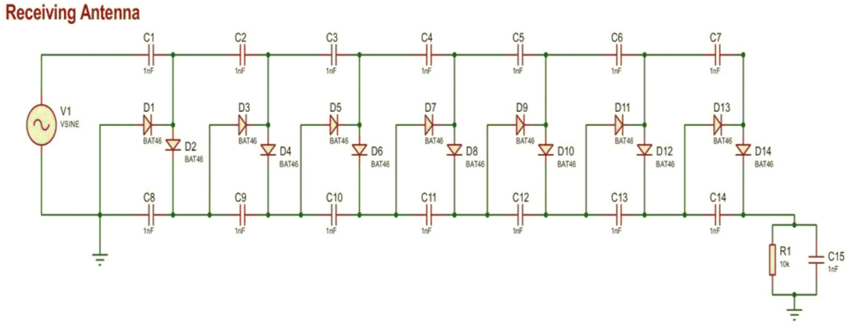

Figure 2: Basic circuit setup of RF-to-DC harvester circuit

2.3. Boost Converter Integrated into the Rectifier Circuit

The boost converter in an RF harvester as shown in Figure 3, transforms a low variable DC voltage from the rectifier into a stable, higher DC output. This step is critical for making RF harvesting feasible for powering practical low-energy electronic devices i.e., temperature and motion sensors, low power microcontrollers, and low power actuators.

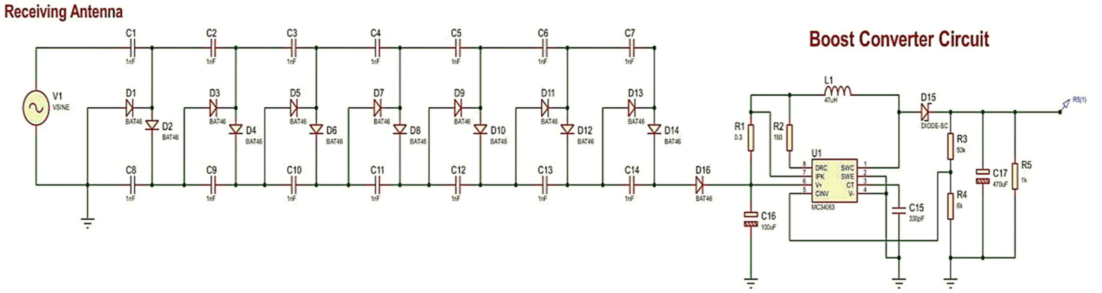

Figure 3: Complete RF rectifier circuit with boost converter

2.4. Simulation of Designed Circuit in Proteus

The simulation phase of the RF harvester circuit design was conducted to assess theoretical performance, optimize component values, and predict expected output under various input conditions. By simulating each part of the circuit, including the RF-DC voltage multiplier stage and boost converter stage, we could identify and address potential issues before physical prototyping.

The simulation was divided into two main stages:

- Assessment of the RF-DC voltage multiplier, focusing on output voltage and efficiency at different input power levels; and

- Evaluation with boost converter, examining voltage step-up capability across varying input voltages. For each test, output was measured across a load resistance of 1k. Frequency sweeps were also performed to determine the frequency response of the circuit.

2.5. RF Rectifier Circuit Development

The circuit was assembled on a vero board with each diode and 1nF capacitor connected to form the desired stages of the multiplier as shown in Figure 4. The vero board layout considers the following: Component Placement: The diodes and capacitors were soldered in alternating pairs along the vero board tracks to maintain stage continuity. Each track connected the anode of one diode to the capacitor and the cathode to the next stage, ensuring the proper cascading effect for voltage multiplication. Minimizing Parasitics: There was careful spacing and minimal wiring in other to ensure reduced parasitic capacitance and inductance, which would otherwise affect performance at high frequencies. This RF harvester voltage multiplier developed on a vero board with diodes and 1nF capacitors have been optimized for converting an RF signal into a DC output. The selection of components and the stage configuration enable efficient energy conversion, and the vero board layout provides flexibility for prototyping and testing.

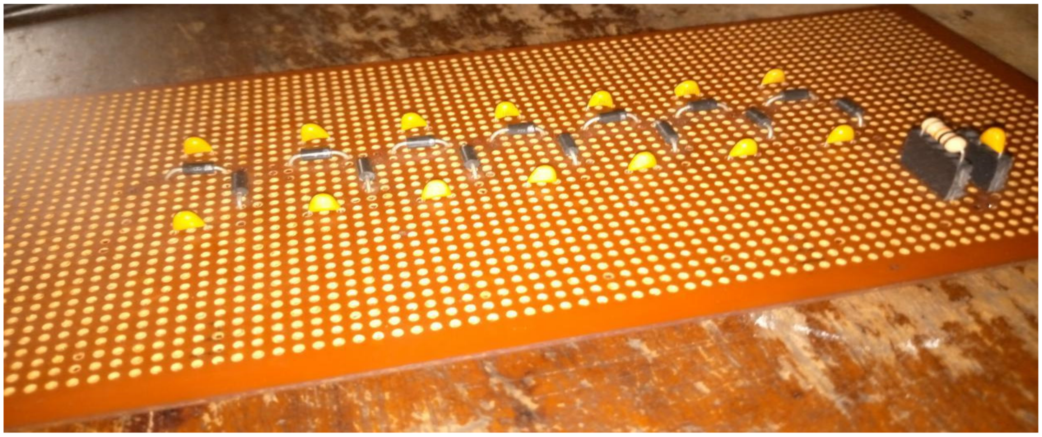

Figure 4: Radio frequency rectifier circuit on a veroboard

3. RESULTS AND DISCUSSION

Table 1 shows the circuit simulation results of Figure 2 at signal frequency of 950 MHz and input amplitude voltage of 1V and recording the values over a stipulated period of time. The 950 MHz represents the ambient RF signal of the GSM 900 frequency while the 1V represents the output from the receiving antenna. The results are well documented in Table 1 which shows that each stage contributes to increasing the total DC output voltage. This step-by-step voltage increment is crucial as it helps accumulate enough voltage to power small electronics or charge energy storage devices. The output voltage at each stage reflects the effectiveness of the circuit in rectifying and amplifying the RF input.

Table 1: Circuit simulation results of voltage multiplier stages

Signal frequency (MHz)	Input boltage V_{in} (V)	Multiplier stages	Output voltage Vout (V)
950	1	1	1.42
950	1	2	2.39
950	1	3	2.91
950	1	4	3.08
950	1	5	3.21
950	1	6	3.22
950	1	7	3.49

Another important characteristic of the RF-to-DC system illustrated in Table 2 shows the result of the simulation performed on the output voltage at different input voltages of 0.3V, 0.5V, 0.7V, and 1.0V for short of period of time. This analyzes the circuit's response across a range of input voltage levels and observe how the output voltage varies with the input strength from the receiving antenna. And it also shows the relative power conversion efficiency (PCE) Figure 8 also shows the plot of the simulated output voltages to the ranges of input voltages at same frequency of 950 MHz.

Table 2: Voltage outputs of RF rectifier based on different input voltages

Signal frequency (MHz)	Input Voltage V_{in} (V)	Output Voltage V_{out} (mV)	Power conversion efficiency
950	0.3	173	33.25%
950	0.5	373	55.65%
950	0.7	559	63.78%
950	1.0	837	70.01%

The RF to DC energy harvester circuit was simulated at an input voltage of 1V connected to a boost converter as shown in Figure 4 to assess its output performance and overall efficiency. The result of the simulation of the rectifier circuit with the boost converter is shown in Table 3.

Table 3: Rectifier output versus boost converter output

Signal frequency (MHz)	Peak input voltage V_{IN} (V)	Rectifier output V_{out} (V)	Boost converter output voltage V_B (V)
950	1	1.42	4.56

The developed rectifier circuit was tested with a 3dBi telescopic antenna connected as receiving antenna was tested outdoors close to a GSM communication mast and it outputted a voltages as shown in Table 4 using a 1 kΩ resistor as load. The maximum voltage that was achieved by th RF rectifier circuit within 25 meters from the communication mast was 0.29V. A reduction of output voltage was observed as the RF rectifier was taken further from the communication mast. The circuit was not used to power any device due to the absence of a super capacitor that would have acted as voltage storage. Figure 5 shows the practical RF rectifier circuit outputting voltage real time in the field.

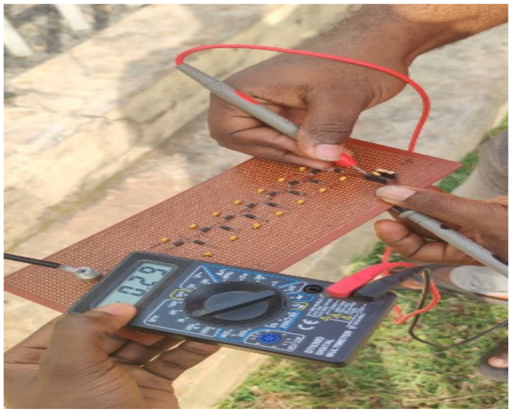

Figure 5: Developed RF energy harvester rectifier circuit outputting voltage real time from ambient RF signals

Table 4: Test results from the practical RF rectifier circuit

Distance from the GSM communication mast (m)	Output voltages from the RF rectifier circuit (V)
25	0.29

Using Equation 2, the power conversion efficiency of the developed RF rectifier circuit was computed.

Output DC voltage, V_o, = 0.29V

Output Resistance, $R_L = 1000\Omega$

Input power (average RF average power from measurements shown in appendix 1):

$P_{in} = 0.20917$ mW

Therefore, power conversion efficiency (PCE) = 40%

Observing the result presented in Table 1, it can be seen that voltage increases steadily with each multiplier stage, particularly from stage 1 to stage 5. After stage 5, the growth in output voltage appears to slow down, showing a leveling-off effect between stages 5 to 7. This graph can be useful for analyzing how effectively each multiplier stage contributes to the output voltage, as well as recognizing any diminishing returns or saturation effects in the later stages. The Table 2 shows a linear relationship between Input voltage and output voltage. The results illustrate how the output voltage changes with increasing input voltage, demonstrating the circuit's performance at different input levels, this suggests that as the input voltage increases, the output voltage also increases proportionally. This result also suggests the potential power conversion efficiency of the circuit. During the simulation, it was noted that the rectifier stage alone provided limited output due to diode voltage drops and inherent circuit losses. However, integrating the boost converter compensated for these drops by stepping up the rectified voltage, demonstrating the circuit's potential for energy harvesting applications. The Table 3 shows that for an output rectifier voltage of 1.42V, the boost converter was able to elevate the voltage to a value of 4.56V, which is capable of providing power to low end electronic devices like microcontrollers, IoT devices etc. This result shows that the output of the RF power rectifier can be improved with about 321% when a boost converter circuit is attached. The practical RF rectifier circuit achieved a power conversion efficiency of 40% which aligns with theoretical results as reported previously (Khan, et al., 2024).

4. CONCLUSION

In this work a radio frequency rectifier circuit that can convert radio frequency signals to DC voltage have been simulated and the practical circuit developed. The results from the simulations showed that the output voltage of the RF rectifier increases with the increases in the number of rectifier stages. The results also show that the output voltage from the rectifier improves with increasing signal strength. It can also be seen from the results that incorporating a boost converter to the rectifier output can greatly increase the output voltage even up to 321%. The results from the practical circuit shows that the PCE of the RF rectifier and its sensitivity improved when the number of rectifier stages is more and using diodes that have low forward voltage drops for the rectifier stages. Further works should be done on optimizing the receiving antenna of the RF energy harvester because it will greatly improve the output voltage of the system.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Alzamil, A. and Islam, M. S., (2022). *Radio Frequency Energy Harvesting Technologies: A Comprehensive Review on Designing, Methodologies, and Potential Applications,* 40(3*)* pp 1100-1114.

Bouchouicha D., Dupont F., Latrach M., Ventura L., (2010). Ambient RF Energy Harvesting. *Renewable Energy and Power Quality Journal,* 1(108), pp 113-127.

Chen , Y. S. and Chiu, C. W. (2017). Maximum achievable power conversion efficiency obtained through an optimized rectenna structure for rf energy harvesting. *IEEE Transactions an Antennas and Propagation,* 65(5), pp. 2305-2317.

Elprocus, (2024). BAT 45 Schottky Diode. Available at: https://www.elprocus.com/bat45-schottky-diode. [Accessed 9th November 2024].

Khan U., Nasir U., Farid U., Farina O., (2024). RF energy harvesters for wireless sensors, state of the art, future prospects and challenges: a review. *Physical and Engineering Sciences in Medicine*, 47(1), pp 385 – 401

Muhammad, S., Smida, A. and Waly, M. I., (2022). Design of wide band circular - slot antenna for harvesting RF energy. *International Journal of Antennas and Prpagation,* 22(2), pp. 9-20.

Muhammad, T. A., Karl-Johan, G., Gullaume, F. and Philippe, L., (2024). Towards zero - energy: Navigating the future with 6G in Cellular Internet of Things.. *Journal of Network and Computer Applications* 55(4) pp. 70 – 87.

Ullah (2022). A Review on Antenna Technologies for Ambient RF Energy Harvesting and Wireless Power Transfer: Designs, Challenges and Applications. *IEEE Access,* 10(2), pp. 82-96.

Wolff, D. D., (2021). The future of the IoT (batteries not required). *MIT News.* [Online]
[Accessed 24 October 2024].

Xu., Wang, P., Niyato, D., & Kim, D. I., 2015. Wireless Charging Technologies: Fundamentals, Standards, and Network Applications. *IEEE Communications Surveys & Tutorials*, 18(2), pp. 1413–1452.

Yunus U., (2016). Design and Implementation of RF Energy Harvesting System for Low-Power Electronic Devices. *Journal of Electronic Material, Vol* 45(8), pp 50 - 67.

Ziyue U., Wilbert O., Ggregory U., (2022). Analysis and Design Methodology of RF Energy Harvesting Rectifier Circuit for Ultra-Low Power Applications. *IEEE Open Journal of Circuits and Systems,* 3(2), pp. 82-96.