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A Brief Overview of Rectifying Antenna Components

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Abstract: The concept of Rectifying Antenna (RA) is not a new one. It is capable of rectifying Radio Frequency (RF) and Microwave back Direct Current (DC), having a wide range of applications in radar development, wireless energy harvesting and many more. Thus, it received the attention of researchers all around the world. From the last few years, the researchers are trying to improve the power conversion efficiency and to reduce the design complexity of the rectifying antenna. This paper mainly deals with the electrical components required in the construction of a Rectifying Antenna. This paper also focuses on a detailed study of antennas and rectifiers.

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1. Introduction

With the growth of human population and their demands in day-to-day life, the demand of energy have also gone high and this will continuously increase in the upcoming decades. At present day, the maximum amount of energy is harvested from non-renewable sources like coal, which causes a huge amount of pollution by emitting greenhouse gases like Carbon Di-Oxide, Carbon Mono-Oxide etc. Recently several countries have started focusing on renewable energy sources like Hydro-Electric power, nuclear power, Hydrogen energy, Wind energy and Solar energy. But these sources are not capable enough to meet the power demands of the growing population. So, researchers all around the world focused on energy harvesting technologies from microwave/radio frequency like wireless power transmission. From then several research works have been performed on the concept of wireless power transmission. The technique of power transmission from Geo-Stationary Orbit (GTO) gains the maximum attention as it causes no such pollution as that of other energy sources does. Such as the efficiency of windmills reduce if the speed of wind increases above a certain limit. Whereas the biproducts/wastes from the nuclear power plants are radioactive in nature and are harmful to humans. At this moment wireless power transmission is the most efficient and reliable source of energy harvesting. But this requires the efficient conversion of DC from the radio waves. This technology requires some of the key components, they are microwave generator, microwave transmitter and the rectifying circuit in the ground station to convert the wave back to DC. This paper focuses on the components of the Rectifying Antenna and how its development started. Sidewise this paper also focuses on the challenges on the path of rectenna development.

A Rectifying Antenna also known as Rectenna, is circuit that can convert radio waves into DC. On its simplest form it has two main components, which are: an antenna and a rectifying circuit. The efficiency of all the individual elements associated with the circuit contributes to the overall efficiency of the system or in other words it can also be said that the more the antenna captures the radio waves, the more is the efficiency of rectification and the more is the overall efficiency of the system. All these are discussed in the below sections and subsections.

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In general, the efficiency of a rectifying antenna is defined as the ratio between the output from the circuit to that of the input to the circuit, and mathematically it can be denoted as:

$$\eta = \frac{P_0}{P_{in}}$$

Here, P_0 is the output power delivered from the rectifying antenna, P_{in} is the input power to the antenna and η denotes the efficiency.

The paper is organized in such a manner that the Section 2 is dedicated to the background of the study, Section 3 includes the study of parts of the rectifying antenna, Section 4 contains the application of rectifying antenna, Section 5 contains the Overall Summery. And last but not least Section 6 is dedicated to the conclusion.

2. Background of Study

The concept of rectifying antenna design came around the late 20th century aiming to be wireless power transmission. But the concept of wireless power transmission was there since 1888. Later in the year 1899 Nicola Tesla made significant development on wireless power transmission. He did successfully transmit power from one place to another, but no arrangements were made to focus the transferred power.

After several years of Tesla’s experiment NASA showed interest towards wireless power transmission around the 1960’s. From then the development of rectifying antenna started and it’s going till date

3. Methodology

As mentioned earlier, rectifying antenna in its simple form has two main components only. But if we look in detail it has five components. They are shown in Figure. 1.

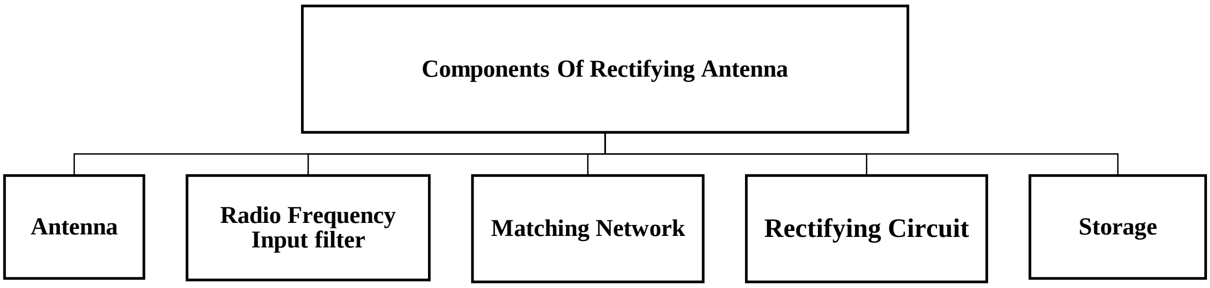


Figure-1 The above chart shows the different parts of a Rectifying Antenna

All these five parts working efficiently contribute to the overall efficiency of the rectifying antenna system. Each of these components are described in detail in the below sub-sections

3.1 Antenna

The design of the antenna is the most crucial, for the efficient operation of the whole rectenna system. The more the antenna captures radio frequency the more the rectification to DC. So, for this reason an antenna must have a wide functioning frequency range, multi-directional radiation pattern, low profile, compact dimensions, high gain and many more. According to their work the antennas are divided into three main parts, they are discussed below:

3.1.1 S-B Antenna

SB antennas, also known as Single Band antenna, are used in operation where there is a narrow single frequency band. There are several parameters upon which the performance of a SB antenna depends, CP (Circular Polarization) is one such parameter and this is used to achieve a stabilized power output. As a stable output increases the overall efficiency of the rectifying antenna. Whereas a CP antenna is unable to detect the CP wave that is reversed. To overcome this problem a concept of duel polarized antenna was proposed. As it was able to detect any type of polarized wave from the surrounding environment. This concept of duel port was implemented where two ports named H-port and V-port were used to detect the polarized signals and a two-port rectification circuit was used to maintain the efficiency of the system.

Apart from CP, another vital parameter of an antenna is its gain. The higher gain of the antenna allows the maximum amount of Radio Frequency to be captured from the surrounding environment, and this parameter is totally dependent on the overall aperture size of the antenna. Also, an antenna with a good gain will be able to detect waves from multiple directions, hence the efficiency of the system will be increased. It was further shown that the gain of the antenna can be improvised by using a reflecting plane at the back of the antenna.

3.1.2 B-B Antennas

B-B antennas, also known as Broad-Band antennas, are designed to operate in broad frequency ranges. These antennas can collect a wide range of frequencies from multiple directions. Several literature papers have been studied regarding the same. It has been proposed that establishing gradual flaring at each bend of the B-B bent triangular antenna strengthen the antenna bandwidth impedance **[1]**. A Paper showed that bandwidth of the antenna can be enhanced by introducing annular slots and rectangular slots on the radiating plane **[2]**. A monopole antenna (CPW) was also studied **[3]**, it suggested that symmetrical slots on each side of the feed line improve the bandwidth of the antenna. In another paper, it implemented a Coplanar Waveguide fed microstrip slotted patch antenna to obtain the characteristics of a broadband **[4]**. In addition, it is also shown that a consequent rotation helps in achieving a Circular Polarization (CP) with a patch antenna array **[5]**. Further Fractal Antenna along with Coplanar Waveguide feeding was studied **[6]**.

The above discussed B-B antennas operate over a wide and broad range of frequency, but it was found difficult in matching the impedance in between the circuits of rectifier and the antenna. The ill-assorted impedance reduces the efficiency of Radio Frequency to DC conversion.

3.1.3 M-B Antennas

M-B antennas stand for multi-band antennas, they are also known as dual band antennas. These antennas cover many frequency ranges making then ideal for implementation in rectifying antennas, and they are capable of more Radio Frequency from the surrounding environment. Several publications have been studied on M-B antennas. Another paper showed that the performance efficiency of S-B antennas is much less than that of the M-B antennas **[7]**. The functioning of slot-loaded antenna in two frequencies are shown **[8]**. A concept monopole, two arms antennas were proposed **[9]**. The lower frequency band was generated by the long arm and the higher frequency band was generated by the shorthand.

In the case of a M-B antenna the receiving power increases as the gain characteristics increase. Several other techniques like A-C (Aperture Coupled) **[10]** and differential **[11]** feeding technologies, antenna array **[12][13]** and air gap technologies **[14]**. These above-mentioned technologies are generally suffering from huge antenna size and its complex design. An antenna with a smaller size could to useful in this state. The circular polarizing property of a M-B antenna helps to receive more stable power. In **[15]** a dual polarized antenna has been proposed.

The above-mentioned dual band antennas operate in several frequencies and capture electromagnetic energy from all the bands. So, they receive more power, and an accurate matching of impedance is relatively better than that of B-B antennas.

3.2 Configuration of Rectifier

The rectifier is one of the vital parts of the rectifying antenna system which converts the captured microwave back to DC. A proper designing of a rectifier element will eventually increase the efficiency of power rectification. Semiconductor devices like diode play a vital role in rectification circuits as they have a large V_{br} (breakdown voltage), lower Rs (series resistance), lower Vth (threshold voltage) and low C_j (junction capacitance).

Usually, a diode having a turn on voltage low and having a higher breakdown voltage are generally chosen for rectifier design. Though, practically this is difficult to obtain a diode with both the characteristics. Along with this, the reverse saturation (IS) current is also an important parameter. When the value of reverse saturation current increases the value of the diode parallel resistance decreases **[16]**. The value of reverse saturation current is dependent on the width of the diode. So, if the diode barrier height is low then the forward voltage drop reduces and the concentration of reverse leakage current increases near the junction barrier. And hence the voltage to turn on the diode becomes low. It has also been noted that a diode with better conversion efficiency has more saturation current. Normal diodes are not used for radio frequencies. Normally the Schottky diodes are used for rectification circuits.

On studying various literature on Schottky diodes for rectifying antenna applications, it has been noted that HSMS28xx and SMS7630 diodes are most frequently used. Generally, the SMS7630 diode is used for designing of rectifiers, where the input radio frequency signal is less than -40 dBm **[8][13][17]**. The breakdown voltage of HSMS28xx varies between the range of 3.8 Volt to 15 Volt, making them suitable for low as well as high radio frequency input **[14][18][19]**. A study of reverse saturation current (I_s), Threshold voltage (V_{th}) and Breakdown voltage (V_{br}) are shown in Table 1.

Model Name	Model Number	V_{th}	V_{br}	I_s
SMS	7630 **[8][13]**	0.09 Volt	2.0 Volt	5.0 µA
HSMS	2852 **[15]**	0.15 Volt	3.8 Volt	3.0 µA
	2850 **[20]**	0.15 Volt	3.8 Volt	3.0 µA
	2820 **[21][22]**	0.15 Volt	15.0 Volt	0.02 µA
	286B **[14]**	0.69 Volt	7.0 Volt	0.05 µA

Based on their configurations, the rectifiers can be classified into two major groups, they are H-W (Half-Wave) rectifier and F-W (Full-Wave) rectifier. These two types of rectifiers are explained in the subsections below:

3.2.1 H-W rectifier

The H-W rectifier can rectify a single cycle of the microwave and further these rectifiers are divided into two more types depending upon the connection of diode to that of the load. They are Series connected H-W rectifiers, and the Shunt connected H-W rectifier. As there is a single diode in a H-W rectifier so the consumption of power is less and thus they are ideal for applications in low power. The implementation of a H-W rectifier for microwave to DC conversion has been studied **[23]**. A Wilkinson power divider enhanced the performance of the rectifier using two H-W rectifiers **[24]**. Another design of an H-W rectifier was proposed using a MA4E1317 diode, the power conversion efficiency came out to be 81% with 30mW/cm2 input power density **[25]**.

We all know that the H-W rectifier is capable of rectifying only the positive half cycle of the microwave. But its efficiency can be improved by injecting the reflected power back to the H-W rectifier. By this way it's power conversion efficiency can be increased by 50% **[26][27]**. Due to the operation of a single diode, the H-W rectifier structure consumes less power and thus the power handling capability of the rectifier is also very low. To overcome these limitations the F-W rectifier was made.

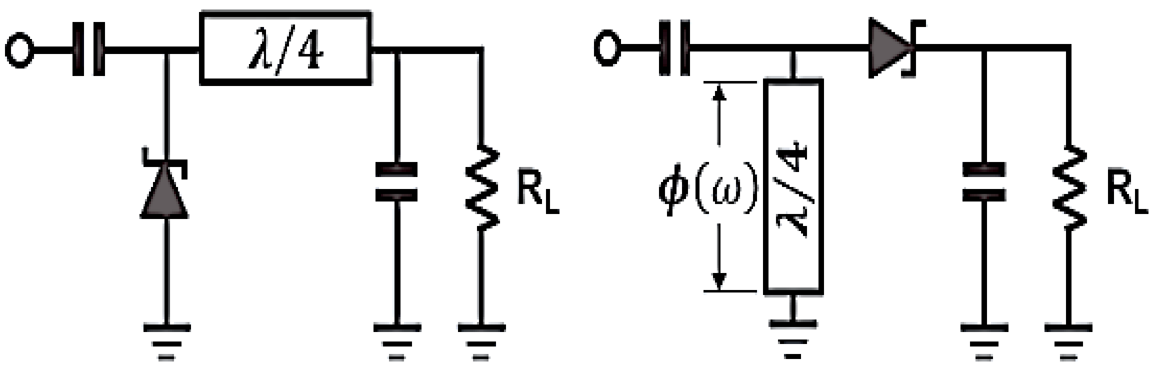
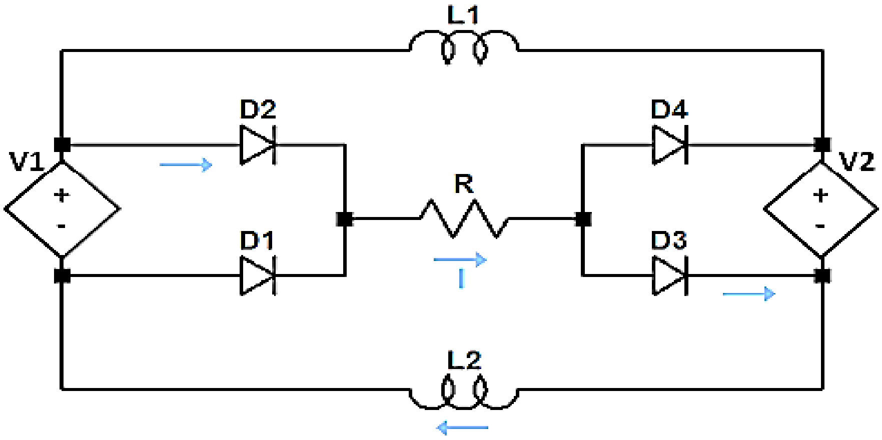


Figure-2 Shows the basic configuration of a H-W rectifier in shunt and series connection.[28]

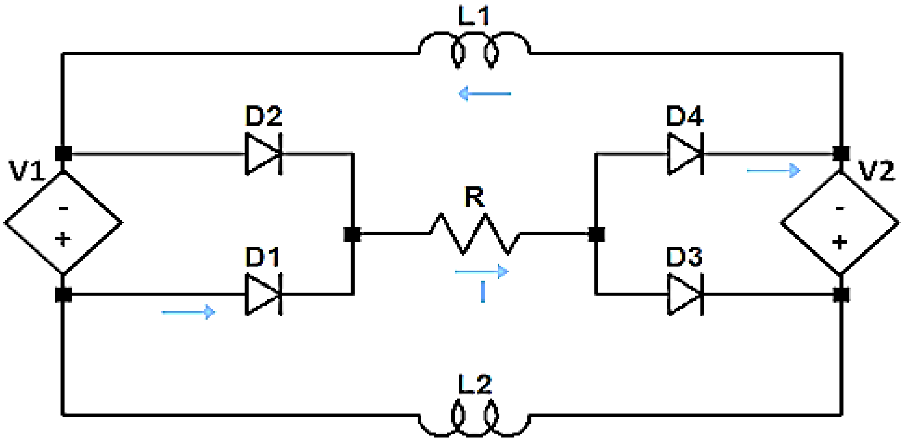
3.2.2 F-W rectifier

In the case of an F-W rectifier both the cycles of the microwave can be rectified. There are some existing configurations of an F-W rectifier, such as F-W Bridge rectifier, Greinacher rectifier and many more. In case of a

F-W bridge rectifier there are four diodes that are arranged in series pairs, each cycle of the microwave uses two diodes for rectification. An F-W bridge rectifier between two dipole antennas was proposed **[29]**. The direction of current is shown in Fig. 3 **[29]**. Here the diodes were fed differentially with a pair of dipole antennas and therefore the efficiency are much more than that of the H-W rectifiers.



(I)



(II)

Fig-3 A F-W rectifier shows the direction of current in case of positive half cycle(I) and negative half cycle (II).[29]

A F-W bridge rectifier structure requires four diodes, this increases the number of diodes, and the losses associated with them. The overall output of the rectifier might decrease on account of the losses of the diodes. Thus, these F-W rectifiers are suitable for input with a large power density. Also, the minimum voltage required for biasing a F-W bridge rectifier is twice that of the H-W rectifier, as there are two diodes connected in a single branch **[30]**. On the other hand, a Voltage Doubler Rectifier circuit charges capacitors from the input source and switches them in a proper way to generate an output voltage twice that of the input voltage. A dual band rectifying antenna with a voltage doubler rectifier were proposed, here the designed rectifier circuit was tuned with two frequency bands **[31]**.

Similarly, to improve conversion efficiency the Co-planer Waveguide configuration was adopted **[32]**. It is also seen that if the voltage multipliers in a cascade connection increases then there is an increase in the overall output voltage **[33]**. Further intensification on rectifying antenna were seen in a Greinacher rectification circuit **[15]** [34-36]. Generally, Greinacher circuit is similar to that of a two staged voltage doubler rectifier connected in the formation of bridge rectifier. The Greinacher circuit has two branches, each branch with two diodes. A general configuration of Greinacher circuit rectifier **[34]** is shown below in Fig. 4.

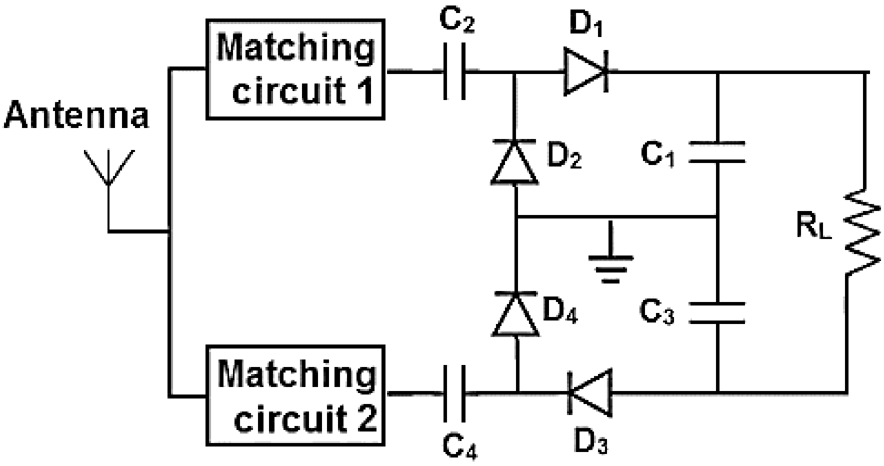


Figure-4 Shows a general configuration of the Greinacher Circuit Rectifier [34].

3.3 IMN and Microwave Input Filter

3.3.1 IMN Configurations.

The IMN stands for Impedance Matching Network, and it is connected between the rectifier and the antenna. The main purpose of using this is to deliver the maximum microwave power to the rectifier that are collected by the antenna. On studying several papers, it is seen that the efficiency of rectifying antenna is much better with the use of IMN **[37]**. It is also seen that impedance matching can also be obtained by reactance transformers (L section network) **[38][39]**. It is easier to match the impedance of a S-B rectifying antenna, whereas it's difficult to match impedance for M-B rectifying antenna.

A M-B impedance matching network with a rectifying circuit is implemented **[31]**. Similarly, a bunch of several rectifying antennas, everyone with a S-B matching network with a rectification topology implemented with a M-B rectifying antenna **[7]**. An impedance matching network with a D-B(dual-band) fourth order was put into practice using L-C, a combination of series and parallel **[40]**. Also, an impedance matching network for a T-B(triple-band) was incorporated using two stubs **[41]**.

It is easy to obtain the impedance matching for a S-B antenna, whereas it is difficult to achieve a proper impedance matching network for an M-B antenna. In case of M-B antennas it is much more convenient to use a bunch of rectifying antennas, each one of them with a proper matching network and a rectifying antenna. The power output of a rectifying antenna can be improved by power combining radio frequency and by techniques of DC power combining **[42]**. The technique of power combination of radio frequency is applicable when the radio frequency generated by a single antenna is low. In this case the combined signal would be able to turn on the diode for effective conversion. Whereas this technique also has a disadvantage, if large powers are received through the combinations, then the impedance matching problem arises. In such a case the technique of DC power combination is used.

The execution of DC combining technique was studied **[43]**. They implemented a three-port pixel rectifying antenna with three-port pixel antenna and a rectification circuit. The main disadvantage of DC power combining technique is the low conversion efficiency from radio frequency to DC and the narrow bandwidth. To deal with the drawbacks of the two techniques mentioned above, the hybrid wideband power combination technique came into action **[44]**. In this technique the antenna gain is improved by performing the hybrid combination.

4. Application for Rectifying Antenna

For the very first time the rectifying antenna was designed for WPT (Wireless Power Transmission) around 1960 by William C Brown. As the concept of wireless power transmission gained momentum, the rectifying antenna also found application in several other fields, such as in WSN (Wireless Sensor Network) in Radio Frequency Identification tags **[45]**, observe the structural condition of a building **[46]**.

Human beings are not free from diseases, they suffer from several health issues related to organs. In such a case it requires continuous monitoring of organs through the sensors they have inside their body. Normal conventional batteries are too outdated for these applications due to their limited battery capacity. The rectifying antenna found its application in this field with continuous powering to the sensors present inside the body. They have several medical applications like deep tissue implantation **[47]**, Pacemakers **[48]**, operating HMDBSD (Head Mountable Deep Brain Simulation Device) **[49]** and many more.

The applications of rectifying antenna are not limited to the medical field only. They found a wide range of applications with the increase in frequency spectrum. Smart cities are totally dependent on rectifying antennas starting from the high data transfer rates to the smart parking systems, smart transportation, smart transportation and many more.

5. Overall Summary

In this paper we have tried to put a brief review on the components of a rectifying antenna. By reading the reference papers, it has been noted that the design of a S-B antenna becomes much easier with an effective impedance matching rectification circuit. The S-B antenna mainly suffers because of its less power capturing and unique operating frequency. While the B-B antennas can capture all the frequencies. Whereas the wide impedance bandwidth reduces the gain of the antenna. Also, it is too difficult to get a proper impedance matching between the rectifier circuit and the antenna hence the rectification efficiency reduces. Generally, B-B antennas either suffer from less power conversion efficiency or less antenna gain.

For rectifiers generally the Schottky diodes are preferred. SMS7630 diode families are used when the power of the radio frequency signal is low, and HSMS28XX diode families are used when the power of the radio frequency is high. From many different rectifier topologies, the Half Wave Rectifier consumes less power compared to that of others because of its single diode operation and, they have low power handling capability. However, to deal with the limitations of the Half Wave Rectifier, the Full Wave Rectifier came into action. These rectifiers are capable of rectifying both the cycles of the radio frequency, but they need a high input to meet the biasing conditions. However, the use of several diodes also incorporates more losses in the bridge rectifier.

The Greinacher circuit are capable of handling high power and as well as they need a less power than bridge rectifier for biasing. However, VDR are the most used rectifier circuit because of their efficient operation in low as well as moderate input radio frequency. The technology of voltage multiplier circuits is also used in rectifier designing. This includes the designing of multiple stages of rectifier to increase the overall output of the rectifier and this topology can be used for low as well as high input power.

6. Conclusion

This paper on rectifying antenna generally tries to give a brief overview on the rectenna components. This also presents the difference between different antenna types, different rectifiers and many more. This review article will also help future researchers to identify the research gap. It can be clearly said that rectifying antenna has the capability to take up the circular polarization, gain of the antenna, radio frequency to DC conversion efficiency. from the reported literature it could be clearly concluded that,

- Mainly slot loaded radiator and single mode feeding/ dual mode feeding approaches help in controlling the circular polarization.
- The gain of the rectifying antenna is generally dependent on the dimensions of the antenna, techniques of feeding and configuration of antenna.
- The conversion of radio frequency to DC depends upon the input of the radio frequency and the rectifier circuit.
- The work on impedance matching networks is too limited. This field requires much more study.

From the authors’ point of view, there are some recommendations. They are:

- Slotted radiators are a better option for circular polarization.
- Multiple layer techniques can be used to increase the overall gain of the rectifying antenna.
- Multiple path power distribution is a better option for M-B and B-B antenna.
- Power conversion from radio frequency to DC could be achieved in a better way with the use of a VDR.

A lot of developments are required in case of radio frequency energy harvesting. The direction of the radio wave is unknown in case of radio frequency energy harvesting. And a very less amount of work has been conducted on rectifying the antenna for energy harvesting. Nicola Tesla conducted a project for wireless power transmission, but his work didn't focus on focusing on the transmitted power. For this technology, we authors have a recommendation of proper sensors. These sensors will orient the antenna in a proper direction, from where the radio waves are coming. But this technology also needs a lot of development. Not only that, but also a proper study of effects on radio waves while passing through earth's atmosphere and environment should also be studied.

We, the authors, have tried to review the paper with most of the data present in the form of literature. Still, we make an apology to the research community if we missed any relevant information from this topic

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8. Conflict of Interest

The author declares no competing conflict of interest.

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