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Article · December 2020

DOI: 10.1109/WSCE51339.2020.9275507

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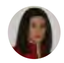

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State-of-the-Art Technologies in RF Energy Harvesting Circuits – A Review

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***Abstract*—Nowadays electricity is undoubtedly one of the most important goods. Over the years, the dependence of people on electrical devices has sharply increased. The need for continuous use of these devices has created greater demand for electricity as well as more efficient transmission techniques. Environmental energy scavenging, as well as wireless transmission, is an increasing research field during the last years. The use of Radio Frequency (RF) Energy Harvesting (EH) technique contributes to the development of autonomous energy devices and sensors, to reduce the need of supplying them with power by using batteries or the mains. In this paper, the state-of-the-art technologies of radio frequency energy harvesting are discussed and analyzed.**

Keywords-radio frequency energy harvesting; wireless power transfer; impedance matching network; voltage multiplier; rectifier

I. Introduction

Energy harvesting (EH) is the process in which energy is collected by the environment and converted into electrical power. The purpose of energy harvesting is the energy autonomy of systems that would normally use batteries or were connected to a power supply network. These systems can be characterized as autonomous energy systems. They can be applied in a variety of applications, such as in the diagnostic and therapeutical field (medical implants) with very low power consumption. Energy from the environment can be solar, thermal, vibration, friction, or radio frequency (RF) signals and behave differently over time, depending on the operating environment of the system. This is the complexity of choosing the right source for each application but also allowing the use of multiple energy sources while increasing the available power. In this paper, we deal with RF EH and the wireless power transfer (WPT techniques as potential sources in autonomous energy systems.

The idea of wireless power transfer has been around since the inception of electricity [1]. William C. Brown in the 1960s with the development of wireless communication technologies developed a rectifying antenna named "rectenna". As a follow-up to this invention, his team conducted several successful experiments in 1968 on the transmission of microwave power [2].

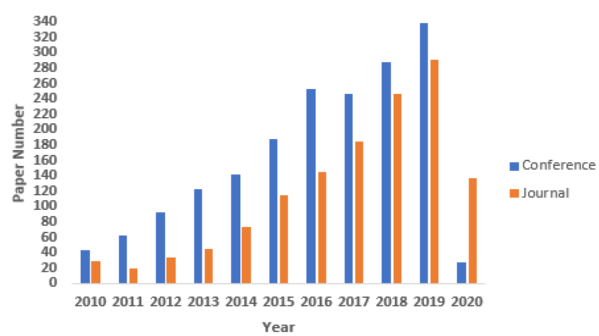

Figure 1. Number of papers referring to RF EH from 2010 until today.

The study of RF energy harvesting and the design of rectenna systems has been the subject of many studies in recent years. A search in the Scopus abstract and citation database of peer-reviewed literature shows that there are 1804 conference papers and 1322 journal papers related to RF energy harvesting from 2010 to 2020. Figure 1 displays the number of papers related to RF energy harvesting for the last 10 years. Additionally, the search in the same database using the keywords RF energy harvesting, reveals a total number of 3235 papers (journals, conferences, and books).

In Figure 2, a complete RF energy harvesting system that consists of a transmission antenna and a rectenna, which accordingly comprises a receiving antenna, an impedance matching network, a rectifier, and a power management circuit, is depicted.

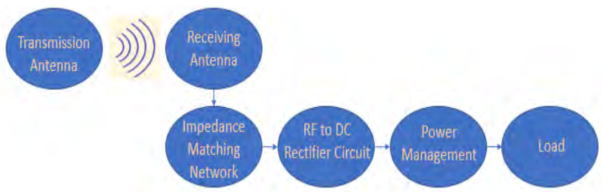

Figure 2. Block diagram of an RF harvesting system

In this paper, we will focus on the design of a rectifier, I which the challenge is the combination of a high output voltage and high-power conversion efficiency for low input power applications. The design methodology includes the following steps:

- The option of the right energy harvesting circuit topology
- The design of an appropriate impedance matching network
- The design and optimization of the total system [3].

The remainder of the paper is as follows. In Section II, the design specifications and the related work are presented. Finally, Section III concludes this review paper with some remarks.

II. Design Specification

A. *Receiving Antenna*

The main function of the receiving antenna is to scavenges as much RF radiation-power as possible, to transfer it to the next stages. The main factors that are taken into account in its design are the gain, the operating frequency, the conversion efficiency of the received power in output voltage, its weight, and size. Antennas are developed in various designs and from various materials. Some of them are bowtie antennas, log-periodic dipole arrays, dipole antennas, monopole antennas, Yagi-UDA antennas, rectangular microstrip antennas, planar inverted-F antennas, etc. Due to the ease of their construction as well as their small size, microstrip antennas (or generally printed antennas) are usually selected.

The authors in [4] - [6] designed and optimized recently various E-shaped patch antennas, having dual or triple band operation in the following desired frequency bands; European LoRaWAN downlink band (863 MHz - 870 MHz), EGSM-900 (925 MHz - 950 MHz) and GSM-1800 (1805 MHz - 1880 MHz) cellular communications downlink band, and UMTS mobile cellular system for networks uplink band (1920.3 MHz - 1965.3 MHz). The proposed antenna designs in all cases exhibit quite satisfactory values of tuning operation and high gain values, thus making them applicable to RF EH applications in the previously mentioned frequency bands.

In [7], an antenna was designed, which can efficiently capture the energy from the ambient RF range of 2.2 GHz - 3 GHz. A compact dual-port L-probe patch antenna is implemented by stacking two single-port patch antennas back to back in [8]. The measurement results show that there is an efficiency greater than 40% for the presented rectenna.

B. *Impedance Matching Network*

Generally speaking, the impedance of the antenna and the rectifier are usually matched at the desired operating frequency, so that the impedances are complex conjugates of each other. An ideal circuit of this type must not only provide the desired impedance matching between the antenna and rectifier but must further do so with minimum losses so that the harvested amount can be maximized [9].

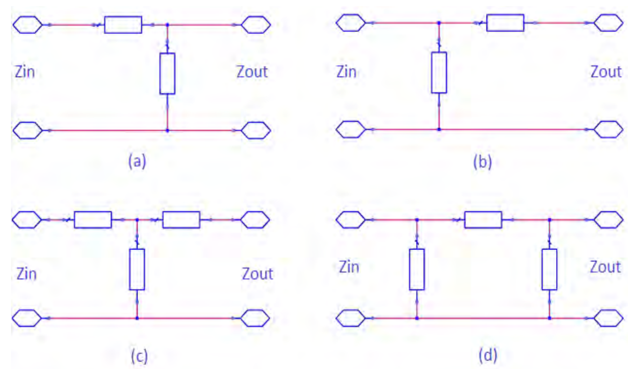

Figure 3. (a) L-network, (b) reversed L-network, (c) T-network, (d) Π-network.

In Figure 3, the four most frequently used matching networks, which are the L, the reversed L, the π, and the T network are illustrated. The selection of an adequate adaptation network depends on the desired objective. The L matching is commonly used since it typically has two components, which simplifies the design process.

The authors in [10] were designed a fully integrated reconfigurable self-startup RF energy harvesting system with storage capability in which it was used as an impedance matching network with lumped elements. The same network designed also by the authors in [11]. In [12] two rectifiers are presented, one half-wave rectifier and one voltage doubler rectifier with the maximum efficiency of the voltage doubler up to 70%. A different matching network with distribution elements is implemented in [13]. The authors tried to make a triband network, but the final result did not confirm them because they did not achieve high efficiencies at each of the desired bands. In [14] though, a triple-band rectifier with open stubs was designed and operated at 1800 MHz, 2100 MHz, and 2600 MHz with conversion efficiency to reach 35% at an input power of -20 dBm. The authors in [15] designed an N-stage rectifier by utilizing a microstrip line network in addition to an L matching network. In [16], a triple-band differential rectenna was presented, which achieved a maximum efficiency of 56% at 3.5 GHz. In a similar way to [16] regarding the impedance matching network, the authors in [17] designed a dual-band rectifier.

C. *Rectifier*

The rectifier is the basic circuit of the rectenna because its role is to convert the AC output voltage of the receiving antenna to DC voltage. It consists of circuit elements (capacitors, coils, resistors) and diodes or diode-connected transistor.

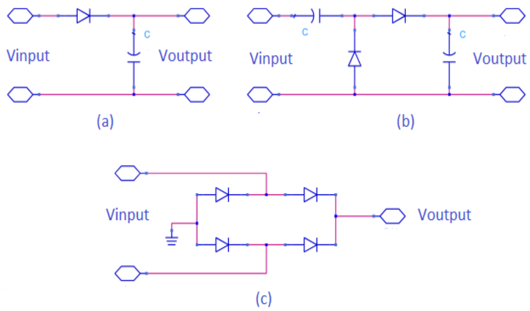

Figure 4. Basic types of rectifier configuration (a) half-wave (b) full-wave (c) bridge.

As Figure 4 depicts, there are three basic types of rectifier configurations, the single diode, the voltage multiplier, and the bridge of diodes. Single diode and bridge rectifiers can provide a DC voltage to the load but the amplitude of the output signals they provide is lower than the received signal amplitude. On the other hand, voltage multiplier is a special type of rectifier circuit that converts and amplifies AC input to DC output. In some cases, a set of stacking single rectifiers into series is utilized (Figure 5), forming a voltage multiplier [2], [21].

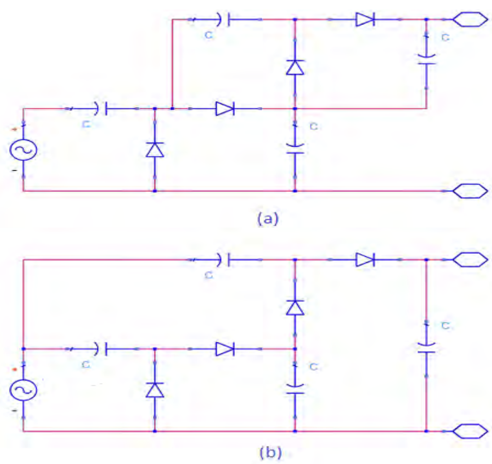

Figure 5. (a) Villard topology (b) Dickson topology

In [22], a single diode rectifier was designed. The authors in [23] designed a rectifier based on the logic of multiplier. Also, to improve the efficiency of their circuit, they placed a coil at the input of the circuit. As a result, they have a performance of 81.65% for 0 dBm input at 868 MHz.

In [24], [25], the authors designed a modified Greinacher rectifier that gets input from one rat-race coupler, which was used to divide the RF signal given from the input into two equal powers with 180° phase shift. In both works, a compact design of the conventional Greinacher circuit was selected by being placed inside the rat-race coupler structure. In [24], the efficiency enhanced over 5% for input ranges from -20 dBm to -10 dBm, whereas in [25], the maximum efficiency is 71% for 4.7 dBm of input power.

A common practice in RF EH systems is to add a boost converter to the output of the rectifier. In [26], the authors designed a low-complexity double diode rectifier which connects to a commercial boost converter. Adopting this practice, they managed to have an efficiency of 21% for input power -15 dBm. The design of a compact rectifier for ambient wireless energy harvesting, which operates in two frequency bands of 2.4 GHz and 5.8 GHz is presented in [27]. It consists of a dual-band matching network and a voltage quadrupler. The reported efficiency is greater than 70% and the system can boost up the voltage level to a maximum output voltage of 9 V. A different structure of a rectifier is presented in [28]. The authors designed a Latour structure, which acts as a voltage doubler. The circuit operates at 850 MHz and has an efficiency of 38% at -10 dBm. Various designs of voltage doublers are presented in [20], [29], [30], [31], [32]. These circuits operate at different frequencies and differ in the choice of materials (capacitors, diodes), and in the substrate as well.

So far, we have analyzed the rectifier circuit consisted of diodes. To overcome the limitations that the diodes introduce to the system, a MOSFET (metal-oxide-semiconductor field-effect transistor) circuit can be utilized. Figure 6 illustrates a 4-stage Dickson multiplier and a conventional differential rectifier. Complementary metal-oxide-semiconductor CMOS technology has been favored by many research groups, because of its comparative advantages (flexible in custom design, sensitive to low operation voltage than traditional Schottky diodes [21]). As a characteristic example, the authors in [33] designed a CMOS Villard multiplier, which operates at 400 MHz and 2.4 GHz. The specific circuit achieves a 160% increase in output power over traditional circuits at 0 dBm of input power.

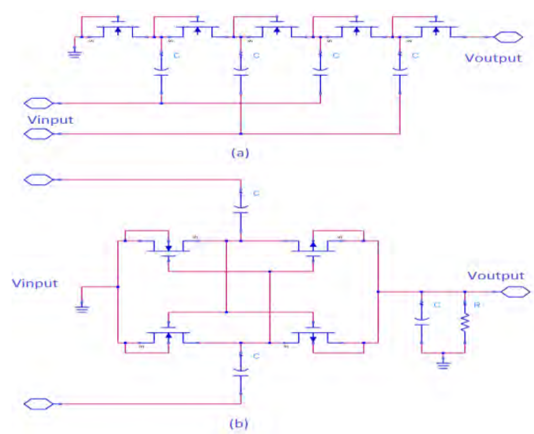

Figure 6. (a) Dickson charge pump (b) Differential voltage multiplier

D. Load

The fundamental parameter that characterizes the quality of a system to RF to DC conversion is the power conversion efficiency (PCE). PCE refers to the amount of energy transferred from the device and is defined as:

$$n = \frac{P_{in}}{P_{out}}, P_{out} = \frac{V_{out}^2}{R_L} \quad (1)$$

where P_{in} is the RF input power, P_{out} refers to the output power with V_{out} as the output voltage and R_L as the output load. To achieve maximum efficiency of the system, the load resistance must be adjusted. From the above equation, we can easily derive the importance of choosing the proper load value. The load can be capacitive, inductive, or purely ohmic. Another remarkable feature of the load effect is that the efficiency of the system decreases when the load increases, [19], [28].

III. Conclusion

In this review, we mainly focus on the radio frequency energy harvesting technique. We have summarized the state-of-the-art RF power harvesting technology during the last 10 years. A basic RF power scavenging unit includes three main modules: the antenna, the impedance matching network, and the rectifier. These components were discussed in detail, emphasizing the design of various topologies of the rectifier.

Acknowledgment

This research has been co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T1EDK-05274).

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