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# REVIEW OF AC-DC RECTIFIER CIRCUIT BASED ON COMPLEMENTARY METAL-OXIDE SEMICONDUCTOR FOR RADIO FREQUENCY ENERGY HARVESTING SYSTEM

Mohd Anuar Rosli, Sohiful Anuar Zainol Murad and Mohd Nazrin Md Isa
School of Microelectronic Engineering, Universiti Malaysia Perlis, Arau, Perlis, Malaysia
E-Mail: anuar_ee87@yahoo.com

**ABSTRACT**

The development of energy harvesting gained much attention in previous decades. This paper reviews the latest research progress on developing the AC-DC rectifier circuits based on Complementary Metal-Oxide Semiconductor (CMOS) for radio frequency (RF) energy harvesting. The various topologies of AC-DC rectifier circuits were reviewed in term of circuit design, technology and performance. The performances criteria such as input power, frequency, output power and efficiency are discussed in details. The overall performances are compared and the best topology of AC-DC rectifier circuit is identified for the future RF energy harvesting system.

**Keywords:** AC-DC, radio frequency, rectifier, energy harvesting, charge pump, CMOS.

## INTRODUCTION

Moving towards a non-stop technologies invention eras, human has gained a lot of benefit in daily life, which are related to their routine work. The increment demand of wireless application gadgets for examples-mobile phones and computers, has shown the important of wireless application in whole world. Alas, the rapid usage of these devices however required the devices to be continuously supplied by battery in order to maintain powering up the device's operating system [1].

Without a doubt, the batteries have a limited life time and hazardous chemicals concern to safety matters. With this, the idea to harvest the energy from the other sources gains attention in worldwide study. The independent sources such as solar, kinetic, vibration, wind, thermal and radio frequency lies around us and can be used as new power sources [2, 3]. Amongst all, the radio frequency (RF) is available and easily found at any places and at any time. RF is an electrical oscillation, with a frequency ranging about from 3 kHz to 300GHz and carrying an alternating current [4-7]. Therefore, by using this concept, the devices such as mobile phones can be used for calling, texting, surfing internet and downloading media while self- charging the battery at same time.

The RF energy harvesting system from RF signal has several level of processing steps. When the system receives the RF signal, which in form of alternating current (AC) as an input and thru the processes the signal is rectified to generate a direct current (DC) voltage output. The ideal RF energy harvesting system should have same power output with the power input for 100% efficiency [7]. However in actual life, this condition could not be found as there will be loss in the processes. Therefore, the goal of the study now is to review the best topology with a maximum efficiency so that the collected RF signal would not be wasted. The other parameters such as frequency range, input power, output voltage and others also should be stressed in the system.

### Circuit topology

Below are several circuit topologies for harvesting RF signal, namely Cross-coupled charge pump, CMOS rectifier, passive multi-stage rectifier and Dickson charge pump.

The first topology is Cross-coupled charge pump. It contains a charge pump, also known as a voltage multiplier is a circuit that converts an AC or DC voltage to a stable DC output voltage. You *et al.* [8] proposed a RF-DC converter that consists of cross-coupled rectifier based on MOSFET and a cross-coupled charge pump. Figure-1 shows a block diagram of proposed converter.

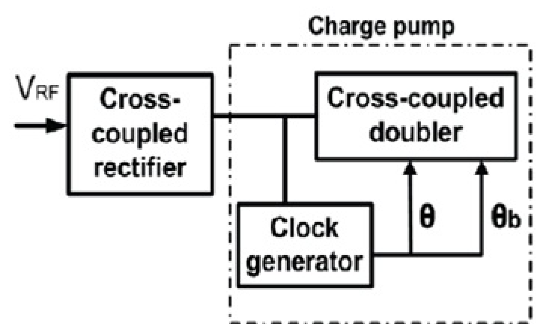


**Figure-1.** RF-DC converter block diagram [8].

The charge pump uses a switching frequency of 25MHz generated by clock generator. The voltage supply for charge pump comes from the rectifier. However a single-stage rectifier is not enough to operate whole charge pump. Therefore the circuit is designed by using N-stage cross-coupled rectifier. Besides, instead using a typical Dickson's charge pump, cross-coupled charge pump is used since it has higher efficiency due to cross-compensation of threshold voltage. The proposed RF-to-DC converter obtains output voltage of 2.05 V at an RF input power of -6 dBm with 100 kΩ load resistance.

The second topology is CMOS Rectifier. The rectifier proposed by Lin *et al* [9] discussed the importance of the optimization of charge pump. Figure-2 shows the block diagram of the test for the circuit to generate a DC supply so the LED can be lighted up.

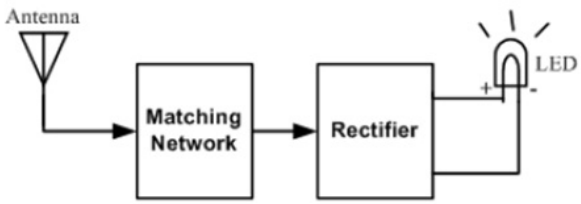


**Figure-2.** Block diagram for energy harvesting system [9].

The threshold voltage, Vth can be reduced by replace the conventional Schottky diode with the diode-connected MOSFETs. The native MOSFET have about 50 to 80 mV threshold voltage, much lower than regular NMOS device. Therefore the efficiency of the system would be optimized. But the native MOSFET have a disadvantage where it has a leakage current that cannot be found in other devices. In order to overcome this problem, and to gain larger ouput voltage, a 5-stage CMOS rectifier circuit is proposed, with optimal MOSFET channel width.

Rastmanesh and El-Masry [10] said that a Vth cancellation technique with an active MOS diode improves the efficiency but the circuit needs a large input voltage that is not available in RF range [11][12]. The threshold compensation technique provides a low power RF harvest but the efficiency reduces due to leakage current in the circuit [13]. This topology however has a solution on both problems, by using an active Vth cancellation with dynamic biasing and a leakage current reduction circuit. Figure-3 shows the proposed one stage rectifier circuit.

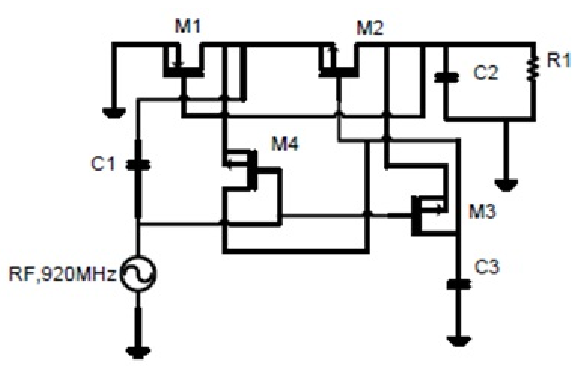


**Figure-3.** One stage proposed rectifier [10].

The full circuit proposed actually have 3 stages, where each stage consists of three PMOS, one NMOS and three capacitors as can be seen in Figure-3. By using this 3-stage CMOS rectifier, the output voltage can be optimized.

The third topology is Passive Multi-Stage Rectifier. Hamid and Moez [14] proposed a RF-DC converter based on passive threshold self-compensated topology. The system is designed to rectify the AC input voltage so the power efficiency can be optimized. Figure-4 below show the proposed back-compensated charge multiplier topology with NMOS-PMOS.

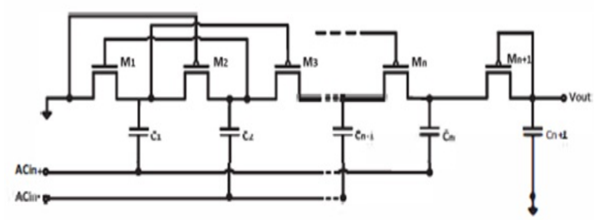


**Figure-4.** Passive multi-stage PMOS topology [14].

A voltage multiplier circuit consists of multiple PMOS transistors in cascade where this circuit reduces the threshold voltage, Vth hence increase the output voltage and efficiency. This multi-stage rectifier eliminates the need of deep nwell technology.

The fourth topology is Dickson Charge Pump. This topology proposed by Ibrahim *et al.* [15], uses a Dickson charge pump-based rectifier with a three stages circuit. Figure-5 shows the circuit where each stage consists of two transistors, a coupling capacitor and a multiplying capacitor.

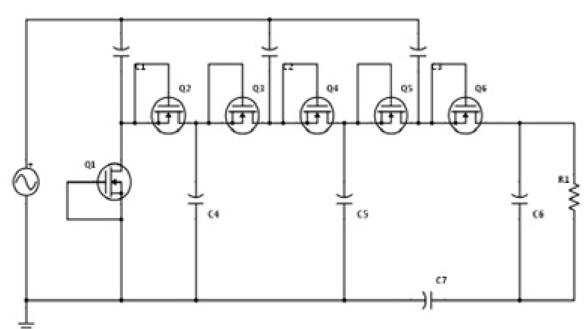

**Figure-5.** 3-stage RF-DC circuit [15].

An RC filter is used in the output stage. voltage from circuits will go through RF filter before going out as a DC voltage. The capacitance values per stage is optimized at -20 dBm input power for frequency of 953 MHz. The proposed rectifier obtains higher efficiency of 94.04 % at -10 dBm input power.

**Summary**

Table-1 shows the performance comparison of all five topologies that have been discussed. Cross-coupled charge pump topology has good efficiency but required higher input power to produce an average output voltage. In contrast, 5-stage CMOS rectifier produced high output voltage; however the efficiency is quite low. Passive multi-stage rectifier and Vth cancellation could not help to get high output voltage and efficiency. However, 3-stage Dickson charge pump is the best topology to obtain high efficiency at low output voltage. The low output voltage produce by this topology may be not sufficient to power up the system.

**Table-1.** Performance comparison of AC-DC rectifier.

| Reference | [8] | [9] | [10] | [14] | [15] |
|---|---|---|---|---|---|
| Technology (CMOS) | 0.13-μm | 0.18-μm | 0.90-μm | 0.13-μm | 0.65-μm |
| Topology | Cross-coupl ed charge pump | 5-stage CMOS rectifier | Vth cancellation | Passive multi-stage rectifier | 3-stage Dickson charge pump |
| Load (kΩ) | 100 | 150 | 100 | 1000 | 12.5 |
| Input Power (dBm) | -6 | -10 | -14.3 | -16.1 | -10 |
| Frequency (MHz) | 900 | 900 | 920 | 915 | 700-2400 |
| OutputVoltage (V) | 2.05 | 2.6 | 1.12 | 2 | 0.5 |
| Efficiency (%) | 63 | 46.43 | 54.5 | 11.4 | 94.04 |

## CONCLUSIONS

A review of AC-DC rectifier circuits for radio frequency (RF) energy harvesting in CMOS technology has been discussed. Based on the previous worked, various topology of AC-DC rectifier have been proposed to obtain high output power and high efficiency. From the comparisons of each topology, it is found that Dickson charge pump topology can produce the highest RF harvesting efficiency with one downside of low output voltage. In the other hand, the cross-coupled charge pump is the best topology in order to obtain high output voltage with high efficiency for AC-DC rectifier design. However, further study is required in order to minimize the input power so that the circuit can receive and rectified more RF signal.

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